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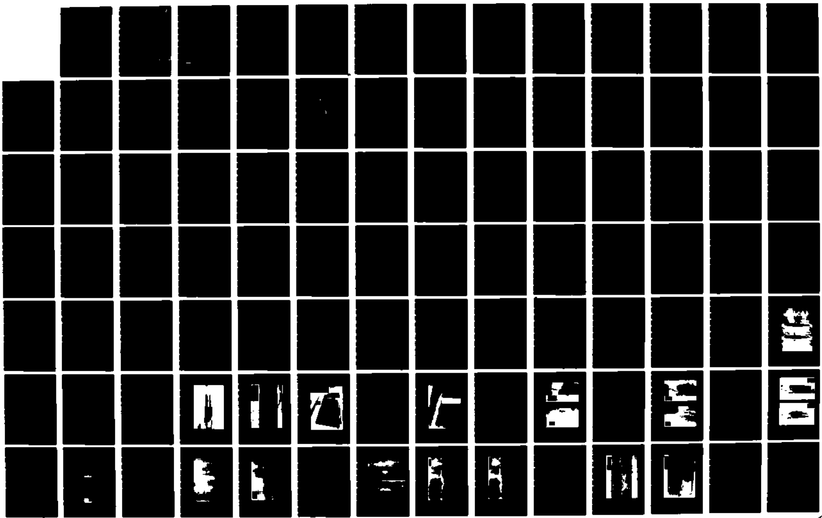

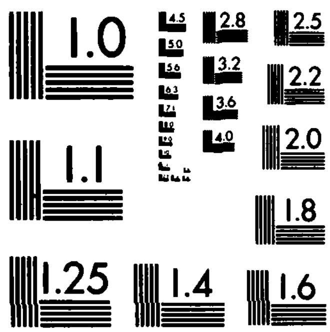

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AN INVESTIGATION OF THE EFFECTS OF DISCRETE WING TIP JETS ON WAKE VORTEX ROLL UP

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Fred Thomas Gilliam, Jr.

August 1983

UNCLASS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER AFIT/CI/NR 83-76D	2. GOVT ACCESSION NO. A135872
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) An Investigation of the Effects of Discrete Wing Tip Jets on Wake Vortex Roll Up	5. TYPE OF REPORT & PERIOD COVERED ~~THESIS/~~DISSERTATION
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Fred Thomas Gilliam, Jr.	8. CONTRACT OR GRANT NUMBER(s) -
9. PERFORMING ORGANIZATION NAME AND ADDRESS AFIT STUDENT AT: University of Tennessee	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS AFIT/NR WPAFB OH 45433	12. REPORT DATE 1983
	13. NUMBER OF PAGES 149
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASS
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 190-17

Lynn E. Wolaver

LYNN E. WOLAVER
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

[redacted]

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I am submitting herewith a dissertation written by Fred Thomas Gilliam, Jr., entitled "An Investigation of the Effects of Discrete Wing Tip Jets on Wake Vortex Roll Up." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Aerospace Engineering.

J. M. Wu, Major Professor

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Vice Chancellor
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ACKNOWLEDGEMENTS

The author gratefully acknowledges the assistance that he has received during this investigation. The opportunity to pursue this educational program was provided by the United States Air Force and that opportunity is deeply appreciated. Special thanks are expressed to the United States Air Force Academy for their sponsorship of the program, to the Air Force Institute of Technology for their interest and support, to the Air Force Flight Dynamics Laboratory for partial funding of the research project, and to the Arnold Engineering Development Center for administrative support. Thanks are also due to the faculty and staff of The University of Tennessee Space Institute for their assistance during the educational program and, in particular, during this investigation. Appreciation is expressed to each member of the Faculty Advisory Committee, Dr. F. G. Collins, Dr. T. H. Moulden, Dr. R. L. Young, and Dr. K. C. Reddy. In particular, very deep and lasting appreciation is expressed to the Committee Chairman, Dr. J. M. Wu, for his total and untiring support and for his valuable advice and encouragement throughout the entire program. The advice and encouragement of Dr. Ahmad Vakili is also appreciated as is the valuable assistance of Mr. Randy Boss and Mr. Dick Ray in conducting the experimental part of this investigation. The support of Mr. Loyd Lester and the personnel of the UTSI machine shop is also acknowledged. Much encouragement and support has been received from friends in the community and co-workers at the Arnold Engineering

Development Center. Particular thanks are due to Mr. Elton Thompson, Mr. Al Boudreau, and Captain Jere Matty for their continual support and encouragement and to Mrs. Judy Wright for her excellent assistance in the typing of this manuscript. Finally, the author is deeply indebted and forever grateful to his wife and children. To Linda, for her unfailing support and encouragement, and to Andy, David, Jamie, and Travis for their patience and understanding, he expresses his heartfelt thanks.

ABSTRACT

A water tunnel experiment and a computational flow field model have shown that discrete wing tip jets can strongly affect the roll up of the wing tip vortex and apparently decrease its rolled up strength at moderate levels of blowing. The key factor in vortex alleviation was the extent of the local flow interactions between the discrete jets and the developing wing tip vortex. Vortex trajectory in both the spanwise and vertical directions was influenced by the jets. An outboard shift of the wing tip vortex indicated that discrete wing tip jets may be able to produce improved wing aerodynamics during cruise flight. The counterrotating pair of vortices generated by a jet in a cross flow were clearly seen in the water tunnel and appeared to be very effective in reducing the intensity of the wing vortex system. Two types of periodic secondary vortices were also observed in the water tunnel for heavy jet blowing. These were "spin-off vortices" which periodically developed in the rolling up tip vortex but rapidly spun outboard and above the wing; and "entrained vortices" which was a set of periodic vortices laterally connecting the wing tip vortex to the vortices embedded in the jet. These secondary vortices are oriented such that they will greatly accelerate the spreading of wake vorticity through the vortex stretching term of the Helmholtz equation. This influence was confirmed in the water tunnel tests. Guidelines for jet configuration design and distribution of jet blowing were developed based on comparison of observed vortex strengths.

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LIST OF SYMBOLS

a	Wing semispan
AR	Aspect ratio
A_j	Cross-sectional jet area at jet orifice
b	Wing span
c	Wing chord
C_{D_i}	Induced drag coefficient
C_L	Lift coefficient
C_μ	Jet coefficient or blowing coefficient = $\frac{2\,\dot{m}}{\rho_\infty}$ [illegible]
dA	Differential element of surface area
dV	Differential element of volume
$d\vec{l}$	Differential element of length along a line vortex
$d\vec{u}$	Differential element of velocity
$\frac{dC_L}{d\alpha}$	Slope of wing lift curve
DY	Initial spanwise spacing of jet vortices = $\frac{\Delta Y}{a}$
DZ	Initial vertical spacing of jet vortices = $\frac{\Delta Z}{a}$
$g_i(y)$	Spanwise distribution of discrete vortex strengths
J	Ratio of jet to cross flow momentum flux
$\dot{m}_j$	Mass flow rate of jet
$\vec{n}$	Unit normal vector
r	Radial coordinate direction, measured from line vortex axis

R	Ratio of jet velocity to cross flow velocity = $\frac{\overline{U}_j}{U_\infty}$
Re	Reynolds number
$\vec{s}$	Position vector with respect to line vortex element
S	Wing area
t	Time
T	Non-dimensional time = $\frac{t\,\Gamma_0}{2\pi a^2}$
$\vec{u}$	Velocity vector
U	Velocity
U_j	Average jet velocity
x	Free stream coordinate direction
y	Spanwise coordinate direction
z	Vertical coordinate direction
α	Angle of attack
γ	Strength of a line vortex
$\gamma(y)$	Spanwise distribution of vortex strength
$\Gamma(y)$	Wing circulation distribution
Γ_0	Circulation at wing plane of symmetry
Γ_1	Initial circulation around a line vortex
δ_j	Jet injection angle
ΔY	Initial distance from wing tip to jet vortices
ΔZ	Initial distance of jet vortex from horizontal plane of symmetry
λ	Angle of dihedral for jet injection
ν	Kinematic viscosity

ρ	Density
$\vec{\omega}$	Vorticity vector
ω_r	Radial component of vorticity vector

Subscripts

c	Wing chord
d	Jet equivalent diameter
j	Jet
∞	Free stream

CHAPTER I

INTRODUCTION

Discrete wing tip jets have been proposed as a method of modifying the flow field in the vicinity of an aircraft's wing tip in order to continually optimize the aerodynamic configuration of the wing. This optimization would be done by varying the amount and direction of blowing during different mission segments. Two important benefits that could result from use of wing tip jets are a minimization of the hazard associated with the wake vortex roll up and a reduction in induced drag, or alternately, an increase in lift to drag ratio. Current interest is high in both of these areas. Wake vortex roll up is a safety problem of major proportion as well as an economic consideration in air field operations, and interest in this area will continue to intensify as air traffic increases. Induced drag reduction has always been important because so many important performance parameters benefit from lower drag. Recent increases in fuel prices have spurred interest and made even the smallest drag reduction a very welcome one.

Thus, the purpose of this investigation is twofold. The primary purpose is to do a feasibility assessment of using discrete wing tip jets as a method of alleviating the wake vortex roll up hazard. An understanding of the flow influences produced by the discrete wing tip jets should be achieved and guidelines regarding jet configuration should be developed. Secondarily, the investigation is

to support other ongoing research on the influence of discrete wing tip jets on induced drag and other elements of cruise aerodynamics.

The investigation included a flow visualization experiment and a computational analysis of the flow field. The main purpose of the experiment was to visually assess the influence of discrete wing tip jets on wake vortex roll up. This experiment was conducted in a water tunnel so that the complex flow field interactions which resulted from discrete jets could be observed and photographed in great detail. The introduction of multiple independent turbulent jets into the very complex three-dimensional flow around about a wing tip is a very challenging problem for computational analysis. Thus the computational model chosen for use in this investigation is a simplified two-dimensional, inviscid model well suited for predicting flow field characteristics but not designed to calculate the details of such a complex interacting flow field. This report will relate this investigation to previous work, present the findings and make recommendations for subsequent research.

The discrete wing tip jet concept was conceived by Professor Wu of the University of Tennessee Space Institute (UTSI), and the current investigation was begun in 1981. Preliminary results (1,2)[1] have been very promising, indicating that discrete wing tip jets, if properly applied, could be developed as a viable means for improving and controlling the wing tip flow field.

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[1]Numbers in parentheses refer to similarly numbered bibliography items.

Alleviating wake vortex roll up problems and decreasing induced drag are two challenging goals to be undertaken. Obviously a great deal of research is needed to determine if discrete wing tip jets are able to make a contribution in these areas. This research is one of the first small but vital steps in that direction.

CHAPTER II

BACKGROUND: WING TIP VORTICES

1. Description of Flow Field

The flow field about a lifting three-dimensional wing is characterized by the roll up of a vortex at the tip of the wing. This roll up is illustrated in Figure 1 which also establishes the coordinate system to be used in describing the flow field. The roll up occurs because of the constraint that there must be no discontinuity in pressure or velocity at the tip of the wing. Physically the overpressure on the lower surface of the wing causes a flow around the tip to the region of underpressure on the upper surface. This vortical motion is superimposed on the free stream velocity and carried downstream forming a part of the trailing vortex system behind the wing. Actually though, the vortex at the tip is just one part of a vortex sheet shed all along the wing span. The constraint that no pressure or velocity discontinuities can occur forces the lift (and thus the circulation) to go to zero at the tips. If the wing produces lift but has zero circulation at the tips, a vortex sheet must be shed at the trailing edge along the span of the wing. The distibution of vortex strength in this sheet depends on the lift distribution on the wing. The trailing vortex system causes a downwash velocity on the wing which causes, in turn, induced drag. Typically, the entire trailing vortex sheet will roll up in the wake

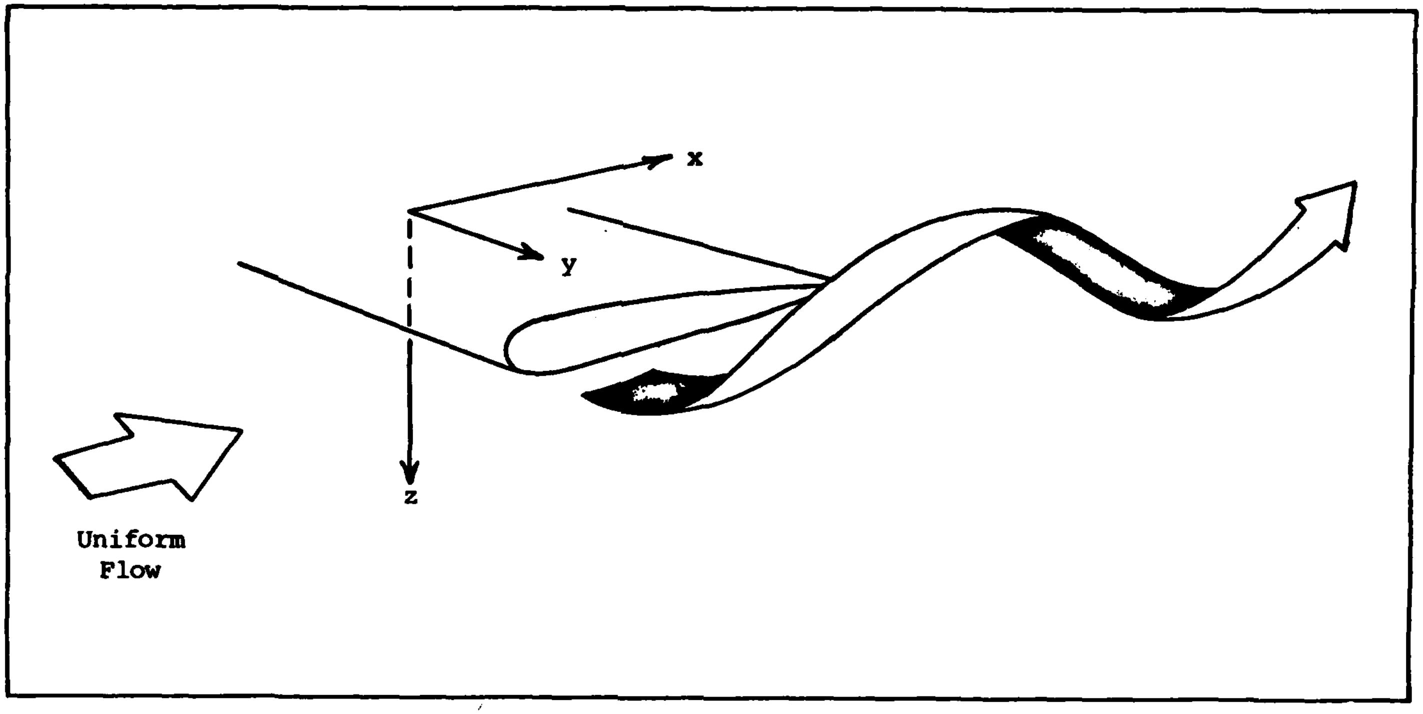


Figure 1. The Wing Tip Vortex

region in a spiraling motion until two concentrated vortices are formed, one behind each wing tip. The trailing vortex system is also a result of the production of vorticity in the boundary layer of the wing. That vorticity, once produced, must remain with the fluid and will, under normal circumstances, become concentrated in the rolled up wing tip vortices. This will be discussed more completely in the following section.

The roll up of wing tip vortices has long been recognized as an inherent part of producing lift and hence an inherent part of aircraft flight. Through the years, however, many wing tip modifications have been designed to reduce the intensity of the wake vortex system. As early as 1925, Reid (3) and others at the NACA were investigating the use of end plates to block the development of the tip vortex. Their goal was to reduce induced drag and improve aircraft performance. This goal remains as challenging today as it was in the 1920's, but another important goal with regard to wake vortex effects has also arisen. The recent introduction of wide-bodied "jumbo" jets has established wing tip vortices as a serious flight hazard.

The primary goal of this investigation was to determine the influence of discrete wing tip jets on wake vortex roll up at low speed, high lift conditions. A secondary goal was to determine the influence of discrete jets on drag production during cruise. The background of these problems and the methods which are available to attack them will be discussed below.

2. Theoretical Considerations of Vortex Decay

The vorticity of an element of fluid is defined as the curl of the velocity vector.

$$\vec{\omega} = \nabla \times \vec{u}$$

If one now takes the divergence of the vorticity vector, it must be identically zero. That is, the vorticity vector is solenoidal. If the divergence of the vorticity is identically zero, there can be no creation or destruction of vorticity in the region which the element occupies. Similarly, by using the divergence theorem, one sees that the flux of vorticity through the surface that encloses the element must also be zero.

$$\iiint \nabla \cdot \vec{\omega} \, dV = \iint \vec{\omega} \cdot \vec{n} \, dA = 0$$

The vorticity which a fluid element contains must have its origin at an interface between the fluid and a solid surface. The vortices behind a wing contain all the vorticity produced in the boundary layer over the entire wing. This vorticity will not be destroyed in the wake but will simply diffuse into the surroundings over a period of time. Thus the topic of vortex decay is not concerned with the destruction of vorticity for such is not possible. Rather, vortex decay is the process whereby the concentrated regions of vorticity are diffused and made ineffectual. The goal of wake vortex alleviation schemes is to accelerate this process.

Accelerated vortex decay is desirable because molecular diffusion of vorticity is an extremely slow process. To demonstrate this the rate of vorticity diffusion can be calculated for a simple flow problem. One begins with the Helmholtz equation of hydrodynamics which is arrived at by taking the curl of the Navier-Stokes equation for constant density, constant viscosity flow.

$$\frac{D\vec{\omega}}{Dt} = (\vec{\omega}\cdot\nabla)\vec{u} + \nu\nabla^2\vec{\omega}$$

Now consider the diffusion of a two-dimensional line vortex which is a potential vortex when time equals zero. Writing the Helmholtz equation in two-dimensional cylindrical coordinates with zero velocity in the r direction and $\vec{\omega} = (0,0,\omega)$, the equation simplifies to

$$\frac{\partial\vec{\omega}}{\partial t} = \nu\left(\frac{\partial^2\omega}{\partial r^2} + \frac{1}{r}\frac{\partial\omega}{\partial r}\right)$$

This is simply the two-dimensional heat diffusion equation; the initial condition to be specified is the strength of the line vortex at time equal zero (say Γ_1). The solution to the equation is

$$\omega(r,t) = \frac{\Gamma_1}{4\pi\nu t}\exp\left(\frac{-r^2}{4\nu t}\right)$$

Since the kinematic viscosity occurs in the denominator of the exponential term, which will always be negative, the decay will be very slow. Using the above solution to calculate circulation as a function of time , one finds that

$$\Gamma = \Gamma_1 \left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right)$$

Circulation remains constant at an infinite radius, but it will gradually decrease at a given finite radius. To illustrate, let r equal 20 feet which is a typical semispan for a general aviation aircraft, and use the kinematic viscosity of air at standard conditions. The time required for the circulation at $r = 20$ feet to decrease to half of its original value is over 220 hours. Winds and other influences would not permit a vortex life nearly so long as predicted, but clearly viscous diffusion is an extremely slow and ineffective method of vortex decay.

Returning to the Helmholtz equation, one can see that the $(\vec{\omega} \cdot \nabla)\vec{u}$ term vanished in the previous calculation as a result of $\vec{\omega}$ being normal to the plane of flow and hence normal to $\nabla\vec{u}$. Unfortunately, a two-dimensional line vortex is a reasonable model of the developed wing tip vortex and $(\vec{\omega} \cdot \nabla)\vec{u}$ could well be insignificant in three-dimensional wing tip vortices. One method of minimizing the strength of tip vortices is to create a flow field such that this term adds greatly to the vorticity time derivative. The term arises from taking the curl of the convective derivative of momentum in the Navier-Stokes equation and has no direct counterpart in that equation. The term is sometimes called the vortex stretching term as it accounts for velocity gradients that are aligned with a component of the vorticity vector. As the flow field becomes more three-dimensional with curved vortex lines and significant velocity

gradients in all three coordinate directions, this term will dominate the vorticity substantial derivative and greatly accelerate the spreading of vorticity.

The results presented in Chapter V show that discrete wing tip jets produce flow field effects that will enhance the $(\vec{\omega}\cdot\nabla)\vec{u}$ term and thus support this theoretical foundation for expecting accelerated vortex decay.

The role of turbulence in the spreading of vorticity is less well defined. Much experimental evidence exists that turbulence can accelerate the "diffusion" of vorticity. However, little data exists on the structure of the turbulence in a wake vortex, and the characteristics of the turbulence no doubt play a role in the spread of vorticity. Research is needed in this area to understand and quantify the effect of turbulence on wake vorticity. Lacking that, the body of experimental data suggests that turbulent mixing greatly affects the structure of the vortex, but the changes which occur may not cause premature vortex decay. Such data will be discussed more completely in a later section.

A consideration of great importance in any investigation of wake vortices is the Biot-Savart law. This law establishes the influence of a vortex on the velocity of any point in the flow field. It states that the increment of velocity, $d\vec{u}$, at a point, p, that is induced by an element of a line vortex, $d\vec{l}$, is

$$d\vec{u} = \frac{\gamma}{4\pi}\,\frac{\vec{s} \times d\vec{\ell}}{|s|^3}$$

where $\vec{s}$ is the vector between $\vec{dl}$ and p and γ is the strength of the line vortex. The net velocity at p can be obtained by integrating the equation along the length of the vortex. The point to be made with regard to the current investigation is that vortices influence each other inversely as the square of the the distance between them. If vortex interaction is proposed as a method of minimizing the effect of wake vortices, that interaction is very weak unless the vortices are brought into close proximity. This fact is evident from a physical standpoint in that a vortex is shed from each wing tip of an airplane, yet their effect on each other is minimal because of the distance between them. Strong interactions occur only when the separation between vortices is small or when vortex merger occurs.

3. The Wake Vortex Roll Up Problem

Magnitude of the Problem

Wing tip vortices are characterized by very high rotational speeds and a remarkable resistance to decay. Dunham, Verstynen, and Benner (4) made measurements behind a C-5A transport and found rotational velocities of 70 feet per second at a distance of 2.5 nautical miles behind the aircraft. Other flight tests by Smith (5) with a Boeing-747 show that the wing tip vortices persist with very little decay in strength at distances of six nautical miles or greater. Light aircraft also create vortices that are very persistent (6) even though the vortex strength is less.

It is the strength and persistence of vortices that make them hazardous to light aircraft. Obviously, rotational speeds of 70 feet

per second are a tremendous hazard to the many light aircraft which have a stall speed of the same order. Typically, a small plane encountering a strong vortex is thrown into a violent rolling maneuver from which it cannot recover. Even aircraft as large as a T-37 can experience a rolling moment behind a Boeing-747 that exceeds available aileron control (5). Similarly, a Lear Jet-23 encountering a wing tip vortex 3.7 nautical miles behind a C-5A was rolled past 270 degrees before the pilot could regain control. During the encounter full aileron was applied to counteract the vortex induced roll but was completely ineffective. This is particularly significant since full aileron on the Lear Jet will achieve a roll rate of approximately 120 degrees per second in clear air (7). Other types of motion including large excursions in altitude and yaw can also result from encountering wake vortices (8).

It is very enlightening to get a realistic assessment of the hazard associated with wing tip vortices. A survey was made of National Transportation Safety Board (NTSB) data for a 10 year period from 1963 to 1974. The results of this review are presented in Reference (9) and show that at least 86 accidents and 48 fatalities during this period were probably vortex related. While this is a significant number, one must also consider that this represents only 0.5 percent of all single aircraft accidents and fatalities. The accident data reveals several interesting statistics regarding the wake vortex hazard. Most accidents occurred near airports. Of the 86 vortex related accidents, 66 were on approach and landing, 18 were

during takeoff and 2 were inflight. The high percentage of accidents near airports can be attributed to congestion and to increased vortex strengths during low speed, high angle of attack flight. Increased air traffic in the future will increase the severity of the hazard unless adequate aircraft separation requirements and the severe economic penalty that they cause are maintained. The NTSB data also showed that the vortex generating aircraft in these accidents were not exclusively large cargo aircraft. The largest number of accidents, twelve, were caused by Boeing-707's and Boeing-727's were next, causing six accidents. But, surprisingly, many accidents were caused by aircraft weighing less than 77,000 pounds, and at least two accidents were caused by aircraft weighing less than 27,000 pounds. The NTSB data is much more consistent for the aircraft which encountered the vortex and crashed. Eighty-five percent of the accident aircraft weighed less than 4,000 pounds and 97 percent weighed less than 11,000 pounds. While, statistically, the hazard is predominately a general aviation problem, two accidents involving larger commercial aircraft also occurred. The most alarming of these was a DC-9 which crashed in 1972 with three fatalities while landing behind a DC-10. The aircraft was on a training mission or the tragedy would have been much worse. With this warning that medium-sized aircraft were susceptible to loss of control in a tip vortex, the NTSB recommended that the Federal Aviation Administration (FAA) increase aircraft separation requirements (10).

The latest FAA separation standards were established in 1975. They require a separation of 3 nautical miles between all aircraft and

separations of either 4, 5, or 6 nautical miles (depending on aircraft weight) when following a heavy jet. These standards have helped reduce the wake vortex hazard but have adversely affected airport utilization and efficiency. In order to meet FAA goals for airport capacity as air traffic increases, these separation distances need to be reduced (9).

Vortex Decay Processes

Total elimination of wing tip vortices is an impossible goal since the production of lift leads inevitably to the shedding of vorticity and the development of vortices in the wake. The best that one can hope to do is to accelerate the natural processes of vortex decay or to alter the vortex structure so that its effect on following aircraft is diminished even though its strength may remain unchanged.

Vortices decay naturally in one of three ways. The first of these is viscous diffusion which was discussed earlier. Viscous diffusion is always present and always involved in the decay process, but rarely does viscous diffusion carry wing tip vortices through the entire decay process. At some point in the viscous dissipation, one of two types of vortex instability will develop and quickly take over and accelerate the decay process.

Vortex breakdown or bursting is a sudden catastrophic change in vortex structure characterized by a very rapid increase in core diameter and a sudden retardation of flow along the vortex axis. Vortex bursts often occur in the flow field over a delta wing aircraft at high angle of attack (11). But despite extensive theoretical and

experimental study of the phenomenon, the processes that lead to vortex breakdown are still not well understood (12). It is evident that a high rate of swirl is necessary for vortex breakdown and a dependence on axial pressure gradient has also been established (13). But with such limited understanding of the triggering mechanism for vortex burst it is not feasible currently to design systems that would excite vortex bursting on aircraft. However, the dramatic alterations in vortex structure seen in flow visualization of vortex breakdown (14) indicates a need to continue basic research on this powerful phenomenon.

Flight tests have shown a bursting type of phenomenon (6, 15), but the breakdown is apparently less abrupt and less violent than seen in Reference (14) or in vortex burst above delta wings. Jones and Chevalier (16) attribute the softening of the vortex burst to the lack of a pressure gradient in the exterior flow. Other inflight observations of vortex burst showed that often one tip vortex disappeared while the other one remained for several minutes (15, 17). Bursting of a single vortex is possible, but decay of a single vortex in the wake of a wing is not characteristic of the other types of vortex decay.

The final type of vortex decay is the development of a sinuous instability first analyzed by Crow (18). As the Crow instability develops, some segments of the vortex pair trailing from the two wing tips will approach each other while other segments move apart forming a wavy pattern. Eventually the approaching segments merge, and the vortex pair becomes a train of vortex rings. The vortex rings then

develop their own instabilities as predicted by Widnall and Sullivan (19) and quickly disintegrate into harmless turbulence. Crow instability decay is well documented by flight test results (6, 15-17); the excellent pictures in Reference (17) clearly show each phase of the decay including the lobed patterns typical of vortex ring instability.

The type of decay that a given vortex will undergo is very difficult to predict. Atmospheric conditions play an important role in both the type of decay and the rate at which it proceeds. Atmospheric turbulence apparently accelerates both viscous diffusion and the Crow instability (15, 16, 20) and high humidity greatly accelerates the decay process (15, 16). A theory developed by Crow and Bate (21) can be used to predict the time for Crow instabilities to develop. The times were calculated for several representative airplanes and are presented in Reference (9). Larger transports have a predicted development time of approximately two minutes which would seem to be an upper bound for vortex life. Observations, however, have confirmed vortices lasting significantly longer. In particular, the surviving vortex after one vortex has burst is immune to the Crow instability and, as mentioned above, is exceptionally persistent. This situation may be the most hazardous of all, and the most likely candidate to require a vortex alleviation system.

<u>Wing Modifications to Minimize Wake Vortices</u>

It has been stated that the development of wake vortices is an inevitable result of producing lift. However, it is equally true that

these vortices rotate in opposite directions, and that at any point behind the wing the net circulation around the entire wake is zero. The operational problem exists because the pair of vortices last for a very long time (or for very long distances behind the airplane) before they decay. But decay will occur eventually, and the goal of wake vortex alleviation schemes is simply to accelerate this process in some effective way.

Interest in alleviation of wake vortices surged during the late 1960's and early 1970's as operational problems due to vortices increased. The resulting research produced a number of candidate alleviation schemes with varying degrees of success. Among the possible ways of alleviating the vortex hazard are methods using nonstandard span loadings, active excitation of the Crow instability, and methods that alter the structure of the vortex core. The rationale which led to each of these alleviation schemes and the effectiveness which they achieved will be briefly discussed.

Nonstandard wing loadings. There are several methods of altering the spanwise wing loading in order to alter the wake vortex roll up. Both theoretical and experimental evidence shows that careful spanwise distribution of lift can provide some vortex alleviation. Two excellent reviews on the theoretical rationale for altered span loading have been given by Rossow (22, 23).

Some candidate span loading alterations have failed to provide vortex alleviation, and, in fact, actually resulted in an adverse impact on following aircraft. A tailored span loading can be

theoretically developed which will cause the trailing vortex system to rotate as a rigid unit, each vortex in the sheet maintaining the same position with respect to the others. Since the vortex system does not roll up in a spiral at the wing tip, one has a completely different wake vortex flow field. Unfortunately, though, the goal of reduced rolling moment on a following aircraft is not achieved. Analysis shows that if the ratio of following aircraft span to generating aircraft span is greater than 0.2, the induced rolling moment actually increases for the tailored loading. A parabolic wing loading studied by Brown (24) also proved to increase rolling moment on a following aircraft. This was surprising since the parabolic loading lowered the maximum rotational velocity in the vortex by over 50 percent. This serves to point out that reduction of induced rolling moment is not a simple problem.

Sawtooth span loadings are those for which the lift per unit span fluctuates from wing centerline to wing tip rather than decreasing monotonically. This has been the most successful method of minimizing wake vortices by span loading alteration. Sometimes the sawtooth loading can be achieved easily by selective use of inboard and outboard flaps. Two theories can be set forth as rationale for sawtooth loadings. Both involve the fact that the sawtooth loading will cause the shedding of both positive and negative vortices on both sides of the wing. It can be shown (22) that a sawtooth loading developed by careful distribution of discrete vortices will cause the trailing vortex system to remain flat and move downward as a unit.

Stability theory shows that small disturbances will destroy the flat wake however, and vortices of opposite sign will pair up and make large excursions from the rest of the wake. Either of these motions would apparently diminish the influence of the vortex strength. The other rationale for sawtooth loadings is that the alternating positive and negative vortices cause the net shed circulation to be zero inside a smaller section of the wing span. Thus the vortices will decay quicker either through viscous diffusion or through development of Crow instabilities.

The use of sawtooth span loadings to reduce the wake vortex hazard has been demonstrated experimentally in both ground and flight tests. The earliest tests were conducted in a water tow tank by Ciffone and Orloff (25). These tests showed that the multiple vortices shed from each side of the wing interacted with each other in Crow-like instabilities. As predicted vortices of opposite sign were observed to pair up and travel out of the wake region. After the system had rolled up into a single vortex on each side, rotational velocities were found to be only slightly lower than for a clean wing at the same lift coefficient. Surprisingly, a wing tailored to unload the outboard section of the wing showed rotational velocities to be reduced by a factor of two. This validated the findings of Mason and Marchman (26) and Brown (24) who had concluded that unloading the wing tip could reduce the intensity of the trailing vortex.

Subsequent wind tunnel and water tank tests by Corsiglia, Rossow, and Ciffone (27) measured rolling moment on a following aircraft as span loading on the generating aircraft was changed. As

suggested by Ciffone and Orloff's findings, the unloading of the wing tip by use of inboard flaps but not outboard flaps was very effective in reducing induced rolling moment. Observation of vortex merging in the wake indicated that vortex attenuation was greatest when multiple vortex pairs were shed with initially large spacing and these vortices were then convected into close proximity. This suggests that the sawtooth loading works best when there are a small number of fluctuations as opposed to a large number. For the stated flap configuration there is only one fluctuation which is of course in the region of the deflected flap. There is a wing tip vortex, a similar rotating vortex on the outboard side of the inboard flap and a vortex originating on the inboard side of the inboard flap but rotating opposite to the other two. The marginal results of the sawtooth loading used by Ciffone and Orloff (25) is consistent with this hypothesis. In that test a series of seven flaps on each side of the wing caused multiple lift fluctuations.

Flight tests confirmed that unloading of the tips by use of inboard flaps only, reduces rolling moment on a following aircraft (5). Unfortunately, it was also found that deployment of the landing gear negated this advantage, returning the induced rolling moment to original levels. Operation at idle thrust, at increased lift coefficient or in a sideslip had the same detrimental effect. Subsequent water tow tank tests with the gear deployed (28) showed that the opposite rotating vortex originating on the inboard edge of the inboard flap was much more diffuse and apparently weakened due to the turbulence generated by the landing gear.

The detrimental effect of landing gear deployment on vortex minimization points out the sensitivity of wake vortex roll up to minor changes in span loading or aircraft configuration. Further flow visualization studies in Reference (28) confirmed this sensitivity, showing that even changes in angle of attack for a given configuration played an important role in determining the character of the wake vortex roll up. The only clear and consistent guideline that was identified was that isolated vortices are very persistent. Ciffone stated "alleviation of wake vorticity is attained by causing the wake vortices to interact and merge" (28).

Active excitation of the Crow instability. Development of the Crow instability depends on the amplification of some initial disturbance. It seems logical to expect that if the aircraft creates a disturbance at the frequency corresponding to the wavelength of the vortex instability and the airspeed of the airplane, the onset of the Crow instability and wake vortex decay can be hastened.

This hypothesis was tested by Bilanin and Widnall (29) using a water tow tank. Oscillation of inboard and outboard flaps such that lift coefficient remained constant provided the disturbance. As expected the sinuous motion associated with Crow instability was created with the oscillations but not without. The surprising result was that vortex breakdown occurred regularly before the Crow instability could proceed to the linking and decay stages. These results were confirmed in flight tests conducted by Chevalier (15). That disturbance was created by oscillating elevator angle at a

prescribed frequency. Once again the Crow instability was initiated but vortex breakdown occurred and interrupted the development.

To be operationally practical, the method of exciting the sinusoidal disturbance must be carefully selected. The elevator oscillatons used by Chevalier is effective, but the resultant porpoising of the aircraft would cause unacceptable passenger discomfort. Kimberlin (30) suggested that oscillating flaps be placed on wing tip end plates in order to reduce the passenger discomfort. Oscillating inboard and outboard flaps as used by Bilanin and Widnall (29) might also be acceptable. However, Crow and Bate (21) point out that these methods would cause small--but possibly acceptable--longitudinal accelerations due to sinusoidal changes in induced drag. Some research has suggested that the Crow instability development can be accelerated by placing the engines such that their exhaust is in the vortex core (31).

The excitation of Crow instability holds a lot of promise for reducing the wake vortex hazard. Recent experiments extended flight test data on the effect of oscillating control surfaces to include large aircraft and showed that induced rolling moment can be greatly reduced (32). However, additional research is needed to find a means of generating oscillatory influences that would be acceptable with respect to airline passenger comfort.

<u>Alterations to vortex core structure</u>. Early attempts at reducing the wake vortex hazard concentrated on altering the structure of the vortex core. Among the methods used were the introduction of

turbulence into the vortex and obstacles to impede the roll up at the tip.

At the first major conference on wake vortex hazards in 1970, several methods showed promise of minimizing the hazard through alteration of vortex structure. A "vortex dissipator" which was a small vertical panel perpendicular to the wing and the free stream generated turbulence in the vortex and produced an expanded vortex core and greatly reduced tangential velocities in the wake (33). Drooped tips were found to reduce the maximum vorticity in the wake (34), and energy arguments indicated that mass injection into the core of the vortex might change the structure such that premature vortex bursting would result. All of these alterations in vortex structure would seem to reduce the hazard to following aircraft. But further research has shown that changing the structure of the vortex and reducing tangential velocities does not always diminish the induced rolling moment on a following aircraft. This brief review will present some of the important lessons learned concerning minimization through alterations in vortex structure.

Several wing modifications are able to reduce circumferential velocities. Poppleton (35) found that a jet blowing into the core of the vortex could do such. Mason and Marchman (36) confirmed this and concluded that introduction of turbulence by any means would spread the vortex core and reduce rotational velocities. This hypothesis has been substantiated by measurements behind crossed blades located at the wing tips (37), porous wing tips (38) and winglets (39). With such

control over vortex structure being possible, it was disappointing to discover that reduced rolling moment on a following aircraft was not being achieved. Snedeker (40) and Dunham (41) confirmed the effect of axial air injection on rotational velocity and core size, but found negligible change in induced rolling moment. Likewise the crossed blades configuration failed to reduce rolling moment (41), and winglets have not yet shown any substantial reduction in wake vortex hazard (42).

The failure of these devices does not mean that the vortex structure cannot be altered such as to reduce rolling moment. On the contrary, Yuan and Bloom (43) developed and tested an unique jet configuration that altered the vortex structure and reduced induced rolling moment by almost 40 percent. These jets blew downward from a tube that extended spanwise from the trailing edge of the wing tip and were beneficial to wing performance as well as in wake vortex alleviation. Thus, the lesson is that a change in vortex structure may reduce the hazard of wing tip vortices, but every change will not do so. Reductions in maximum rotational velocities and enlargement of the vortex core are good indicators, but measurement of induced rolling moment is currently the most meaningful way to gauge alleviation of the vortex hazard. Other criteria such as the downwash imposed on a following aircraft will become more important as alleviation schemes enable roll control to be maintained.

Other methods of altering vortex structure through turbulence injection have also shown promise. Patterson and Jordan (44) showed that the rolling moment generated by a Boeing-747 model could be

reduced by directing the engine exhaust into the vortex core. The greatest vortex attenuation was achieved by operating inboard engines at one-quarter power reverse thrust and outboard engines at full power forward thrust. Similarly spoilers have proved to reduce induced rolling moment both in wind tunnel (45) and flight tests (32,46). Deflection of outboard spoilers will unload the wing tips as well as produce turbulence. It might be expected from the findings on span loading effects that outboard spoilers would provide the greatest vortex attenuation. This was not indicated by the wind tunnel tests, but was a conclusion drawn from the more limited flight test data.

The last method of attenuating wake vortex roll up is the use of wing fins to inject additional vortices into the wing wake. This method combines several of favorable influences which have been found. It can be used to redistribute wing lift, inject turbulence into the flow field, and create additional vortices to accelerate the decaying process. Rossow (47) conducted a theoretical and wind tunnel study of the wing fin effect in 1978. The theoretical results showed that midspan injection of a vortex rotating opposite to the trailing vortex system would tear and then disperse the vortex sheet. Surprisingly though, the companion wind tunnel tests showed that induced rolling moment was reduced only when the injected vortex rotated in the same direction as the wing system. The optimum strength of the injected vortex was 20 to 30 percent of the wing circulation and the fin was much more effective on the upper wing surface as opposed to the lower wing surface.

Additional research by Rossow (48) showed that fins with a semicircular planform were more effective than rectangular ones. Also two smaller fins located close together performed better than a single fin. The best spanwise location of the fin was near midspan and rolling moment would increase above no fin levels if the wing fin was too far inboard. Croom and Holbrook (49) expanded the data base on wing fins and found that the flow over the fins was separated and turbulent as was the flow on the wing behind the fin.

The use of auxiliary vortices is a very promising technique for reducing the wake vortex hazard and needs to be fully explored. The wing fin would, of course, impose a drag penalty on the aircraft, and one would have to accept degraded cruise performance or design a system for fin retraction. In lieu of wing fins it might be possible to produce an auxiliary vortex through a system that improves rather than degrades cruise performance. Discrete jets such as those investigated herein are a very promising way of doing just that.

4. Effect on Aerodynamic Performance

The physical constraint that there be no pressure or velocity discontinuity at the wing tip and hence that there be vanishing lift at the wing tip works to degrade overall wing effectiveness. The goal of many previous wing tip modifications was to enable a pressure differential (and hence lift) to exist at the wing tip. This is illustrated in Figure 2 where a pressure discontinuity has somehow been created and maintained outboard of the physical wing tip. The lift force in this area does not act on the wing, but the nonzero

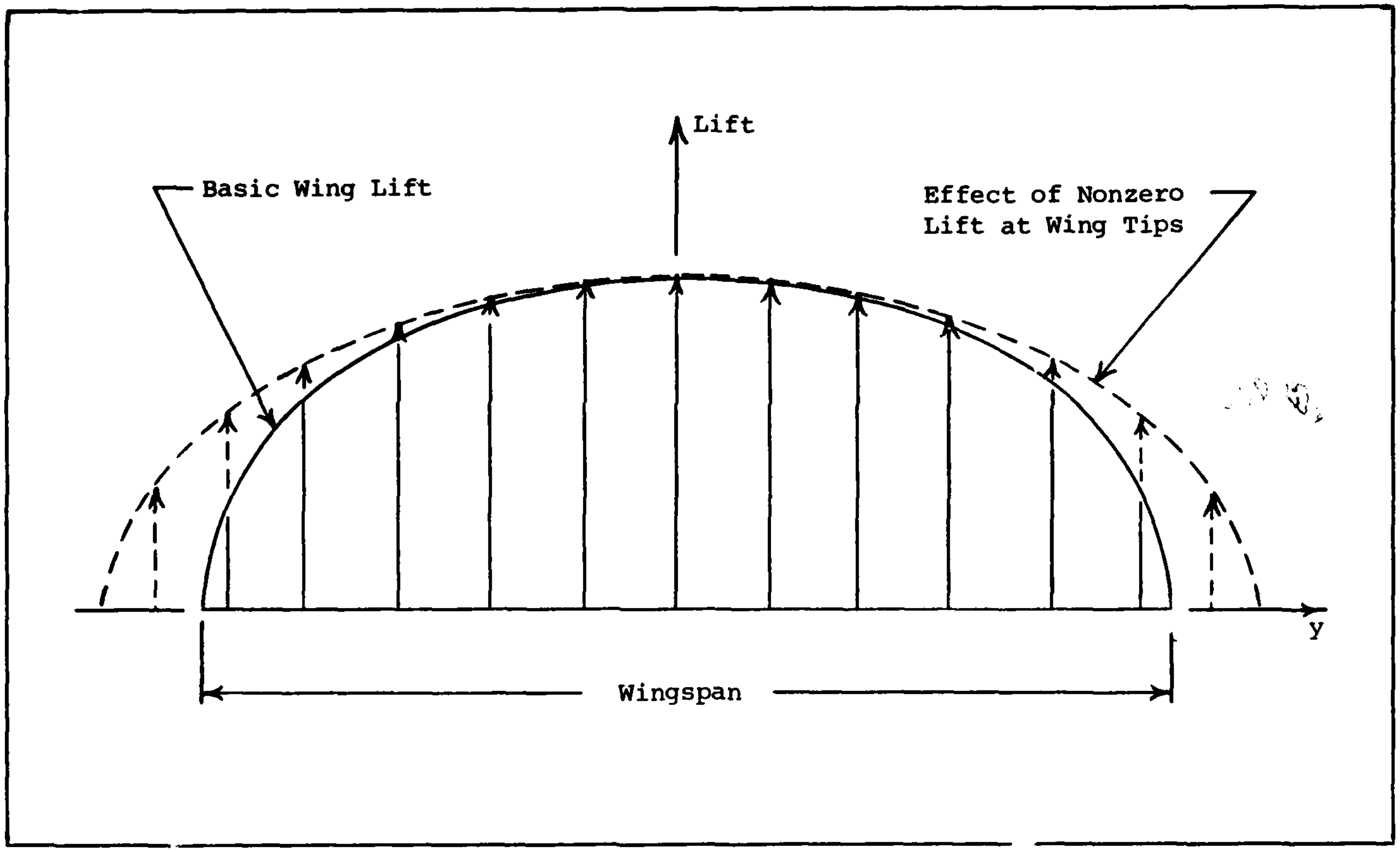


Figure 2. Effect of Nonzero Lift at Wing Tips

lift at the tip and the increased lift along the outer portion of the span does provide a dramatic increase in wing lift. Conversely, if the lift is held constant, the vorticity shed from the wing would be spread over a greater distance and consequently the downwash at the lifting line would be decreased. This would then result in decreased induced drag. Reductions in profile drag would also be realized since the additional lift provided would allow flight at lower angles of attack. The net effect of nonzero lift at the wing tips is very similar to an increase in the wing aspect ratio and changes of this sort are called an "effective increase in aspect ratio." The dependence of the lift curve and induced drag on aspect ratio is seen in the following basic aerodynamic equations:

$$\frac{dC_L}{d\alpha} = \frac{2\pi}{1 + \frac{2}{AR}}$$

$$C_{D_i} = \frac{C_L^2}{\pi AR}$$

Obviously, the effects of tri-dimensionality become more pronounced as aspect ratio decreases or as the wing configuration progressively loses its resemblance to the infinite span case.

Tip Modifications for Aerodynamic Improvement

End plates. An end plate located at the tip of a wing is a logical way of disrupting the flow from the lower surface to upper surface and producing nonzero lift at the tip. This idea was first

tested in the 1920's, and the results confirmed the hypothesis that end plates could improve wing aerodynamic performance (3). The report showed that at higher lift coefficients ($C_L > 0.3 \times C_{L_{max}}$), the end plates provided a substantial reduction in induced drag. And as expected, the end plates also caused an increase in the slope of the lift curve versus angle of attack. From that promising start, end plate technology grew rapidly due to extensive experimental and theoretical study by Hemke (50) and others at the NACA, Mangler (51) and others. In the 1940's the emphasis with respect to end plates shifted from wing applications to the use of an end plate on the vertical tail (52). The horizontal stabilizer was located at the top of the vertical tail in an arrangement which is familiar now as the "T tail." A more thorough review of end plate development is given by Kimberlin (30).

End plates are currently used in many applications. The success of the T tail, in particular, is vividly demonstrated by the scores of modern airplanes which employ that design. End plates are also seen on a limited number of airplane wings, on the horizontal stabilizer of some helicopters, and on the blades of some commercial windmills. The limited use of end plates on airplane wings is primarily due to the fact that an increased aspect ratio was very often a more efficient way to achieve the same result in a particular design. End plates did contribute however to advances in wing technology. End plate research was very valuable in understanding the flow field at a wing tip and from this understanding came a major advance in wing design, the winglet.

Winglets. The most effective wing tip modification yet developed for lowering airplane cruise drag is the winglet. Winglets appear very similar to end plates and grew out of the same design philosophy, but the drag reductions provided by winglets are far greater than end plates can provide. This indicates a major improvement in management of the wing tip flow field.

Winglets are small nearly vertical winglike surfaces located at wing tips. The primary winglet surface is located above the wing on the aft part of the chord. Smaller, secondary surfaces are located below the wing and forward. The critical difference between winglets and end plates is that winglets are carefully designed lifting surfaces, not merely a flat plate used as a flow impediment. The importance of this difference was discovered by Whitcomb who recognized that "to be fully effective the vertical surface at the tip must efficiently produce significant side forces" (53). Production of a side force benefits performance in two ways. Firstly, the flow field associated with side force production will have reduced inflow on the upper wing surfce and reduced outflow on the lower wing surface. This results in increased lift on the wing. Secondly, careful design and location of the winglets will result in a side force on the primary winglet surface that has a thrust component directly offsetting drag.

The aerodynamic thrust of the winglet and the more efficient lift production of the main wing combine to give winglets a dramatic improvement in aerodynamic performance. Wind tunnel tests on a first

generation, narrow body, jet transport model showed that the addition of winglets reduced induced drag by 20 percent and increased lift to drag ratio by 9 percent. These improvements were at design Mach number and design lift coefficient and were significantly greater than was achieved by extending the wing span. End plates have never achieved such impressive improvement at lower lift coefficients. Very often the additional parasite drag of the end plate would offset reductions in induced drag to give marginal change in net cruise drag.

Additional wind tunnel studies of winglet performance have confirmed their usefulness in reducing cruise drag (39). But, the most forceful evidence of the benefits winglets can provide are seen in flight tests of a winglet equipped KC-135. These tests showed that winglets improved fuel mileage during cruise from 4.4 percent to 7.2 percent depending on weight and cruise altitude (54). Fuel burn is, of course, the most meaningful measure of cruise performance. The induced drag reduction of winglets impact fuel burn favorably, but the additional parasite drag of the winglets and the small increase in aircraft weight are also taken into account. It is interesting and encouraging to note that the improved cruise performance available through winglets would result in approximately 37 million gallons of fuel saved annually for the KC-135 fleet (42).

Winglets have already been employed on several airplanes including small general aviation craft such as the Rutan Vari-Eze and corporate jet aircraft such as the Gates Learjet Longhorn. The improvements seen on smaller craft are also very dramatic (55), and it

is expected that winglets will become much more prevalent in the future.

Despite the excellent performance of winglets, they are limited in some respects. The greatest limitation is the fact that winglets are rigid structures designed to optimize the aerodynamic characteristics at a single design point. Off design operation can diminish their effectiveness, and at some flight conditions the winglets can actually be detrimental to performance. The fact that fuel mileage improvement varies between 4.4 percent and 7.2 percent is self evident that optimum performance is not always achieved. This is in contrast to the variable wing tip configurations which one observes on birds in flight. Hertel (56) demonstrates these variations with an excellent series of photographs and drawings. It is expected that if similar flexibility could be added to winglets in a simple way, their performance improvements could be made even more substantial. The use of discrete wing tip jets in combination with winglets could possibly provide the needed flexibility.

CHAPTER III

BACKGROUND: AERODYNAMIC JETS IN CROSS FLOW

The history of aviation is inextricably intertwined with the aerodynamic jet. Jets have always been used to generate propulsive forces, at first via propellors, later through gas turbines and rockets. As aviation progressed designers realized that jets could also help solve aerodynamic problems by providing aerodynamic control. Very often a jet can be directed such that it will entrain the surrounding fluid and ensure that a desired flow pattern is maintained. The control that a jet can provide is well illustrated by the wide range of jet applications on modern aircraft. Among these are jet flaps, boundary layer blowing, spanwise blowing, and augmentor wings.

Interest in vertical takeoff and landing (VTOL) aircraft has spurred much of the recent work on aerodynamic jets. One design concept that has received much attention is direct jet lift. In this concept the reaction force from a jet located on the bottom of the wing would provide lift for takeoff. The jet would then be slowly rotated to transition the aircraft to forward flight. During the transition process, the jet would be subjected to a nearly normal cross flow. A great deal of research has been conducted on this flow field supplementing earlier basic research on the topic.

The first significant study of a jet with a cross flow was conducted by Callaghan and Ruggeri (57) in 1946. This and other early

studies were primarily concerned with measuring jet trajectories for various jet shapes. Later work began to concentrate on understanding the physics of the jet and cross flow interaction. The work by Jordinson (58) and Keffer and Baines (59) are particularly notable in this regard. A more complete review of the development of jet in a cross flow technology is given by Keffer (60). From the work reviewed therein and subsequent research, the flow field of a jet in a cross flow is quite well known. The characteristics of this flow field will be discussed and the use of jets at the tip of a wing will be reviewed.

1. Description of Flow Field

The majority of research on a jet in a cross flow has dealt with a round jet exhausting from an infinite flat plate. This geometry is appropriate to VTOL application and in addition is simple enough to facilitate analytical investigation. The primary flow characteristics seen in more complex discrete jet geometries are very similar to the round jet flow field described below.

The flow pattern for a jet exhausting into a normal subsonic cross flow is shown in Figure 3. The jet can be divided into three regions. The names of these regions are not uniform in the literature, but their characteristics are quite distinct. The names used in Figure 3 follow the very excellent description of the flow field given by Pratte and Baines (61).

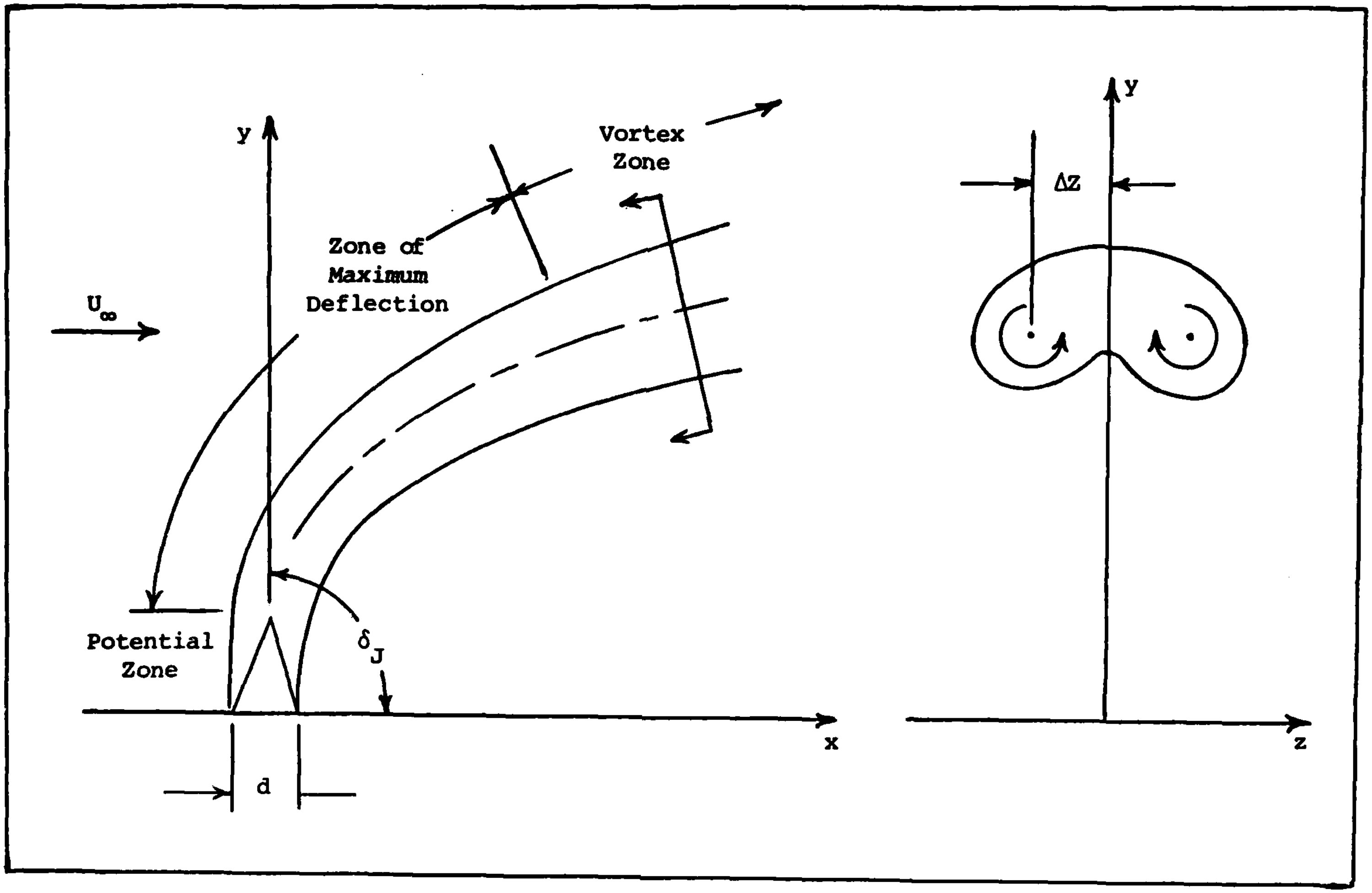


Figure 3. Jet in a Cross Flow

In the potential zone there is intense shear between the jet and the cross flow. The edges of the jet are decelerated while the surrounding fluid is entrained and accelerated. The turbulent shear grows into the jet until the entire cross-section is affected. This is the end of the potential region. The flow patterns in this region are described very nicely by Pratte and Baines.

> In the potential zone the streamlines are essentially parallel to the jet direction, and the cross flow is affected in the same manner as if a solid cylinder were present. The small entrainment velocity moves fluid toward the jet at the sides and a separation occurs just behind the maximum width. In the wake, the mean velocity is much smaller than in either jet or cross flow and two vortices can be seen, exactly as found in flow around a cylinder at low Reynolds number. These vortices are not shed because of the longitudinal motion induced by the jet entrainment velocity. A typical particle's path is an upward spiral.

The zone of maximum deflection is, as its name implies, the region wherein the jet is turned to be aligned with the cross flow. Mixing between the jet and the cross flow is intense and the entrainment causes a steady increase in effective jet diameter. Once again the description of Pratte and Baines is excellent.

> This region is characterized by a rapid decrease of mean velocity in the jet. In a relatively short length the jet is moving in a direction only a few degrees different from the cross flow, and no longitudinal relative motion between the two flows can be detected. The twin vortices, however, do not reduce in strength, and are the dominant feature at the downstream end of this zone. . . . The vortices must be receiving vorticity from the jet-flow interaction because the size increases steadily and the angular velocity changes little.

The final region as described by Pratte and Baines is dominated by the two counterrotating vortices which have been developed. These

vortices will be a very important consideration with respect to how discrete wing tip jets affect wake vortex roll up.

> In the third region, the two turbulent vortices are carried along at the cross flow velocity. The profile continues to rise at a slow and decreasing rate, the vortices increasing in size along with the jet cross section, but decreasing in angular velocity. This zone is defined as the vortex zone and no end has yet been observed for it.

Eventually the vortices must decay through viscous diffusion, but this occurs very far downstream. Pratte and Baines cite wind tunnel observations of the vortex zone 1000 jet diameters downstream of the jet source.

The strength of the counterrotating vortex pair is an issue of primary concern. Kamotani and Greber (62) measured velocities in a deflected jet and found that the velocity distributions, and hence vortex strengths, depend mainly on the ratio of jet to crossflow momentum flux, J.

$$J = \frac{\int \rho_j \, u_j^2 \, dA_j}{\rho_\infty \, U_\infty \, A_j}$$

At low values of momentum flux (J = 15.3), they found the jet to be bent so sharply that the vortices do not have time to develop and are everywhere weak. Higher values of J gave stronger and more persistent vortices. Fearn and Weston (63) quantified the strength of the counterrotating vortices for a round jet exhausting into a normal cross flow. Using measured velocities in a vortex cross section, they were able to calculate vorticity normal to the cross section. This data is presented as a function of effective velocity ratio, R, which

is the square root of the momentum flux ratio, J. If one assumes that u_j is constant across the jet orifice, that the pressure in the jet at the orifice equals p_∞, and that $\rho_j = \rho_\infty$, then R is simply the average jet velocity at the orifice divided by free stream velocity

$$R = \frac{\bar{U}_j}{U_\infty}$$

The findings of Fearn and Weston support a slight modification to the jet description as given by Pratte and Baines. The maximum vortex strength is apparently established very near the jet orifice and is directly proportional to the speed of the jet and its diameter, both taken at the orifice. The vortices are then deflected and diffused as a function of arc length along the jet. The data by Krausche, Fearn, and Weston (64) extends the earlier data to include the effects of jet injection angle. They found that at the higher effective velocity ratio (R = 8) vortex strength increased regularly and significantly with increasing jet injection angle (δ_j in Figure 3). For the lower value of R (R = 4) no comparable change was found. The spacing between the counterrotating vortices (Δz in Figure 3) and the vortex core size were also found to increase with increasing jet injection angle.

2. Previous Wing Tip Jet Studies

Wing tip jets have been used previously to improve aerodynamic characteristics. The most common configuration previously studied was a jet sheet located at the wing tip, blowing outward, and extending

continually across all or most of the chord. The jet sheet is a fluid extension of the wing and will support a pressure difference across it when placed at an angle to an oncoming stream. The pressure difference and hence the lift on a segment of the sheet can be related to the radius of curvature of the sheet (65). This lift force is not transmitted to the wing of course, but the nonzero lift at the tip is a source of significant improvement. The aerodynamic effects seen will be much the same as end plating, that is, an effective increase in aspect ratio. The wide, thin jet sheet does not produce the pair of counterrotating vortices which were discussed earlier.

The influence of the jet is a strong function of the jet momentum. The ratio of jet to cross flow momentum flux, J, is an inadequate parameter for comparing jet effects on wing performance. A more valuable parameter called jet coefficient or blowing coefficient, C_μ, is commonly used.

$$C_\mu = \frac{2\ \dot{m}_j\ \overline{U}_j}{\rho_\infty\ U_\infty^2\ S}$$

where $\overline{U}_j$ is the average jet velocity at the jet orifice.

Lloyd (66) and Carafoli and Camarasescu (67) have both made experimental investigations of the jet slit configuration described above. In each case the jet was installed on a straight, low aspect ratio wing. As was shown in Chapter II, low aspect ratio wings are most sensitive to changes that create an effective increase in aspect ratio. This sensitivity and the very large jet coefficients which were used produced very impressive wing performance improvements. The

jet coefficients tested in both experiments usually exceeded the airflow normally available from either jet engine bypass or compressor bleed. Nevertheless even the lower jet coefficients, which are operationally feasible, showed results well worth pursuing. Lloyd tested a wing with an aspect ratio of two and found that at moderate angles of attack ($\alpha = 5.2°$) and a realistic value of jet coefficient ($C_\mu = 0.2$), lift was increased by 34 percent over the zero-blowing case. Lloyd calculated the effective aspect ratio which the jet blowing achieved and found it to be 2.6 for $C_\mu = 0.2$. At extremely high jet coefficients ($C_\mu = 2.51$), lift to drag ratio could be increased by a factor of two at moderate angles of attack. Carafoli and Camarasescu tested several low aspect ratio wings and found even larger lift increments.

Two additional tests of wing tip jet sheets have been conducted. Scheiman and Shivers (68) tested a straight wing with an aspect ratio of 3.4 to see if wing tip blowing could alter the location of the downstream vortex core. A grid and tuft system was used to determine vortex position in the wing wake. The photographic data indicated no change in vortex position up to the maximum jet coefficient tested ($C_\mu = 0.054$). Changes in vortex core structure were not discernible either. Additionally Scheiman and Shivers made force measurements for the wing and jet sheet. They found that a jet coefficient of 0.054 produced a small increase in lift and small increase in drag at the same angle of attack. A jet coefficient of 0.007 did not affect wing force data.

More recently Briggs and Schwind (69) have investigated the use of a wing tip jet sheet to reduce takeoff and landing distance of advanced fighter aircraft. Their study included the effects of wing taper ratio and jet shape. Very narrow jet slits were less effective at increasing lift at lower jet coefficients ($C_\mu < 0.1$) than were thicker jets which varied jet thickness proportionately to wing thickness. Conversely at higher jet coefficients the thin jets were more effective than the thicker ones. The aerodynamic force data was used to analyze the effect of jet blowing on takeoff and landing distances for an F-15. Ground roll reductions of 15 percent for both takeoff and landing were predicted by the analysis.

While studies of wing tip jet sheets have shown them to have very beneficial effects, a major concern exists regarding the magnitude of blowing required to achieve the aerodynamic improvement. This is especially true with regard to high speed cruise performance where the cross flow momentum flux is correspondingly high. Genuine performance improvement at cruise will be realized only if jet airflow demands--which must be supplied by the engines--are minimized. This will require optimizing jet configuration to the greatest extent possible, and is comparable to the extensive optimization which winglets required in order to realize the benefits which the concept promised. The application of wing tip jets to wake vortex alleviation will also require an optimum jet configuration. The lesson to be learned from wing tip jets and other wing tip modifications is that success in either reducing wake vortex roll up or improving cruise performance is extremely sensitive to configuration detail.

3. Discrete Wing Tip Jets

The concept of discrete wing tip jets has been envisioned as a means of providing additional wing tip flow field control beyond what can be achieved by either wing tip jet sheets or rigid modifications. This additional measure of control results from two influences. First, as illustrated in Figure 4, the discrete jets can be independently controlled with respect to direction and amount of blowing. This enables each jet to be designed such that it creates the desired flow characteristics in the small region of the flow field where its influence is the strongest. The second influence providing additional control is the occurrence of the counterrotating vortex pair which are characteristic of a jet in a cross flow. It is expected that these vortices will interact with each other and with the wing tip flow field to produce favorable results. It has already been shown that the production of auxiliary vortices and their interaction with the primary wing vortex system can be an effective measure in alleviating wake vorticity (2[illegible]). It is also interesting and very encouraging to note that the only jet configuration which has demonstrated a capability to reduce induced rolling moment — the downward blowing jet of Yuan and Bloom (43) — was also the only jet configuration which would be expected to produce a counterrotating pair of vortices. Finally, the discrete wing tip jet will generate considerable turbulence in the wake roll up region. While not a flow control mechanism, controlled turbulence is very beneficial in

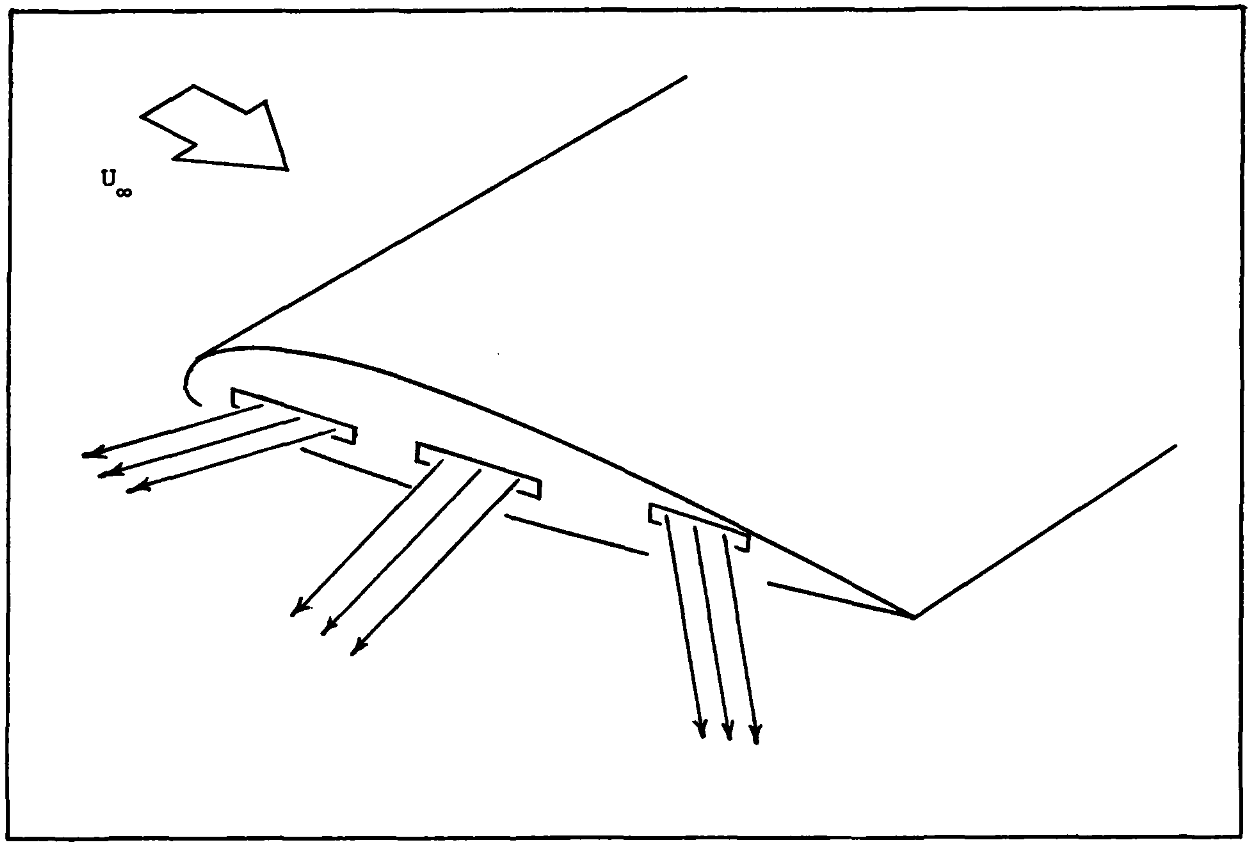


Figure 4. Discrete Wing Tip Jets

accelerating vortex decay through either Crow instabilities or viscous diffusion (16).

From the standpoint of aerodynamic improvement, previous work has shown that discrete jets can support a pressure difference at the wing tip and provide an increase in lift in a manner similar to jet sheets (1,2). It is postulated that this change in aerodynamics would also result in reduced downwash and reduced induced drag due to the effective increase in aspect ratio which has previously been discussed. Hopefully the discrete jets can be optimized such that induced drag reductions comparable to those supplied by jet sheets can be achieved at lower jet coefficients.

In addition to conventional airplane wings, discrete wing tip jets could also be applied on rotary wing aircraft. Alleviation of tip vortices is an important goal in that situation due to the vortex impingement or blade-slap problem.

CHAPTER IV

DESCRIPTION OF EQUIPMENT

The experimental investigation of discrete wing tip jets was conducted in the University of Tennessee Space Institute (UTSI) Water Tunnel. The water tunnel tests provided flow visualization data on how the jets affect the wing tip flow field and the near field wake vortex roll up process.

1. Wake Vortex Testing Methods

Test Facility Considerations

The use of wind tunnels to measure scaled forces is the foundation of most aeronautical testing and the scaling laws that must be observed are well known. The use of ground test facilities to simulate and study wake vortices is not nearly as common and scaling requirements--though well established--are not widely appreciated.

Several types of ground test facilities are required in order to fully evaluate the effectiveness of wake vortex alleviation schemes. The ultimate question to be answered in testing is whether the induced rolling moment on a following aircraft model is reduced when that model is at a scaled distance typical of actual vortex encounters. Stickle and Kelley (70) reviewed the capabilities of four major facilities used by NASA in vortex research. These included two wind tunnels, a water tow tank, and an air tow tank. Wind tunnels can make accurate measurements of induced rolling moment, quickly

surveying large portions of the wake to determine the regions where rolling moment is maximized. Also, the unlimited run time available in a wind tunnel permits the data to be temporally averaged in order to quantify the influence of vortex meandering or other unsteadiness. But even very large wind tunnels are unable to correctly scale encounter distance. Tests in the NASA Ames Research Center 40 foot by 80 foot wind tunnel were conducted with the rolling moment probe located 15 span lengths behind the vortex generating model (70), an encounter distance much smaller than practical flight cases. Tow tanks using either air or water as a medium can measure induced rolling moment at correctly scaled encounter distances (44, 48), but these facilities produce data far less efficiently than wind tunnels. Because of the relatively small test time per run and the delay between runs necessary to allow the fluid in the tank to return to quiescent conditions, it is a lengthy process to survey the wake in order to locate and measure the maximum rolling moment. Meandering of the vortex due to unsteady influences is also present (48), and will introduce additional uncertainty unless several repetitions of each run are made.

This investigation has used a water tunnel to study the effects of discrete wing tip jets on the wake vortex roll up process. Water tunnels, like wind tunnels, are limited to small encounter distances, and accurate measurements of induced rolling moment in a water tunnel are extremely difficult or impossible to achieve. The strength of the water tunnel, however, is the excellent flow visualization which it

provides enabling the experimenter to see in great detail the structure and interactions of very complex flow fields. Dominant features of the flow field can easily be identified, and anomalous flow phenomenon that might never be pictured in the mind nor predicted theoretically become apparent. Such a graphic display of the structure of the flow field is a tremendous aid to the experimenter in understanding both the behavior of the flow field and its effect on bodies immersed in it. As one observes the effect of various mechanisms for alleviating wing tip vortices, one learns how and why each mechanical or fluid device alters the structure of the flow field. This understanding of flow field cause and effect can then give direction for further improvements in the vortex alleviating mechanism. These improvements can then be tested in a wind tunnel or water tow tank to determine if, in fact, they reduce induced rolling moment. This is the value of water tunnel testing.

In this experiment the near field wing tip vortex development was observed and photographed for regular wings and for wings with discrete wing tip jets. This initial development of the vortex is very important because it will influence the vortex characteristics along its entire length.

Scaling Considerations

It has been concluded that the modeling of wake vortex phenomena in water is governed by scaling laws that are essentially the same as those governing wind tunnel testing (71). As long as cavitation is avoided, and the phenomena to be modeled are

incompressible, the similarity achieved in the water tunnel depends primarily on Reynolds number effects. The kinematic viscosity of water is about 1/15 that of air at normal temperatures, and hence the Reynolds number is 15 times greater in water than in air at the same scale and speed. However small scale models and low fluid velocities offset this advantage, and water tunnel Reynolds numbers are generally much lower than is achievable in wind tunnel facilities and lower still than aircraft in flight.

Test Reynolds numbers in this experiment (6.0×10^3 to 2.7×10^4) are significantly lower than realistic flight cases. Fortunately, previous tests have found that the observable character of wake vortices does not depend on Reynolds number. Comparisons between water tow tank experiments and flight test wake photographs have shown close agreement in wake appearance (28). Additionally, Iversen has developed a correlation of wake vortex rotational velocity data from water tow tanks and from flight test developed that clearly demonstrates the similarity of the two data sets (72). Additional data by Tartaglione has confirmed this correlation (73).

The vortex roll up process as photographed in this experiment provided detail that has not been achieved in flight test photographs, and thus comparisons are not possible. However, because of the apparent insensitivity of vortex flows to Reynolds number effects, it is reasonable to assume that the wake vortex phenomena seen in this experiment are representative of actual flight conditions.

The appropriateness of water as a medium for studying jet phenomena has also been established. Forstall and Gaylord (74) showed

that the diffusion of momentum and material for a water into water jet was similar to air into air jet characteristics under incompressible conditions. Also Pratte and Baines (61) established that jet trajectories for a jet in a cross flow is independent of Reynolds number (for Re > 1.0×10^3). Prior use of the UTSI Water Tunnel for studying jet phenomena has been very successful (75, 76).

2. Water Tunnel Facility

The UTSI Water Tunnel is a closed circuit, continuous flow facility especially designed for high quality flow visualization. Major components of the facility are illustrated in Figure 5. The circuit of the tunnel lies in a horizontal plane with the test section and a portion of the return circuit enclosed in a building. The test section is 12 inches high by 18 inches wide by 60 inches long and is constructed primarily of Plexiglas for versatility in observing and photographing the flow. Test section walls diverge slightly in the flow direction to maintain constant free stream velocity as the wall boundary layer thickens.

The tunnel is powered by a 1 horsepower electric motor connected via a variable speed transmission to a 10 inch diameter, twin-bladed propeller in the return leg of the circuit. This system permits continuous variation in test section velocity from 1 inch/sec to 20 inches/sec. Tunnel velocity has been related to propeller rotational speed via measurements with a hot film anemometer. This calibration was verified by Sheikholeslami (77) immediately prior to

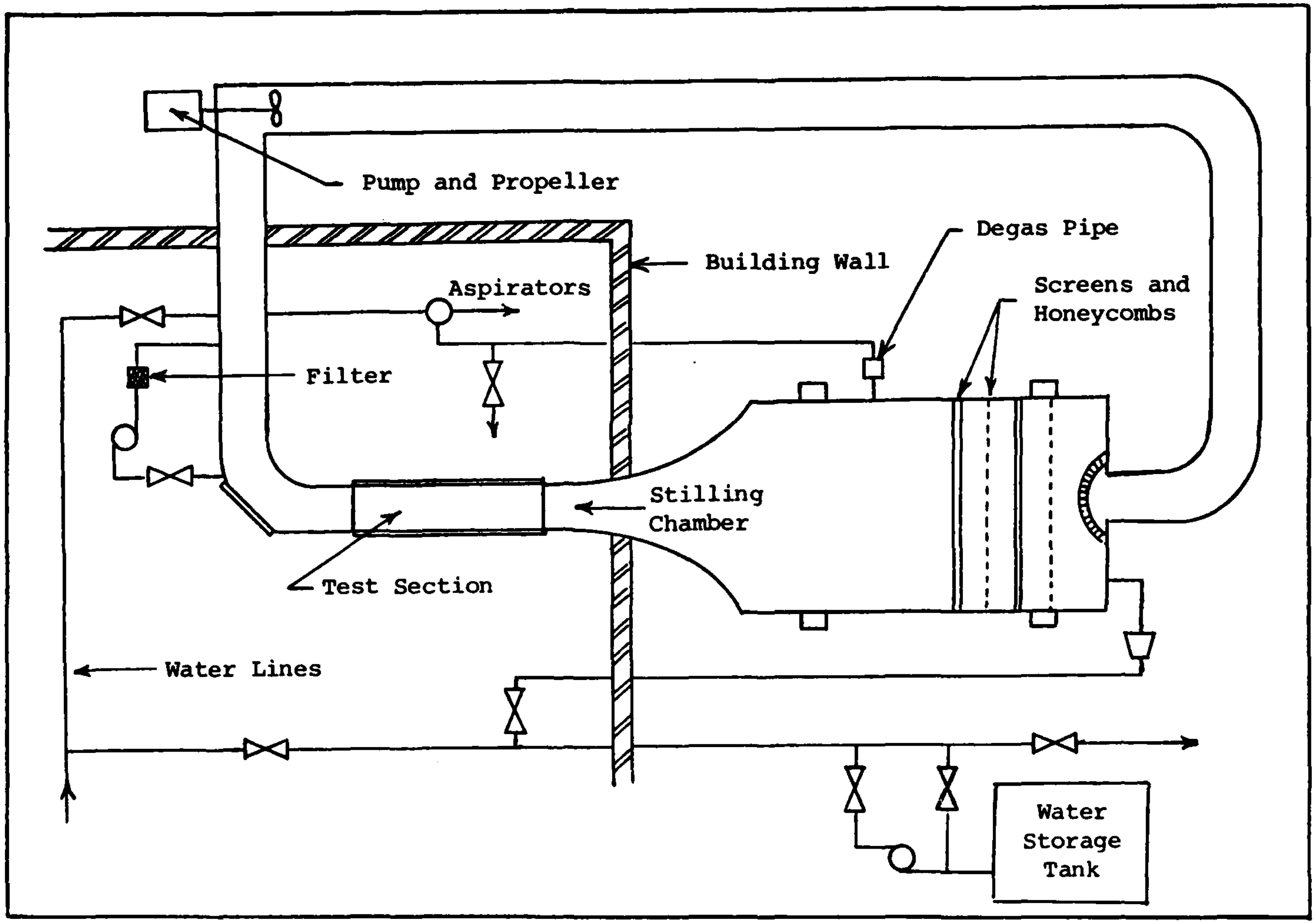


Figure 5. UTSI Water Tunnel

these tests, and that data was used to infer free stream velocity from measured propeller shaft rotational speeds.

Various turbulence controls throughout the circuit provide the very low turbulence levels necessary for good flow visualization. Fluctuations from the propeller are damped by the long return pipe (equivalent length/diameter = 75) leading to the stilling chamber. The stilling chamber contains 4 stainless steel screens and 2 aluminum honeycomb sections to minimize test section turbulence. The bell mouth nozzle has a contraction ratio of 13.5 to 1 and changes smoothly from a circular to a rectangular shape.

The low turbulence and large windows in the UTSI Water Tunnel enable excellent photographs to be made of flow phenomena, and extensive photographic data was taken during this experiment. The flow field was recorded by color prints, black and white prints, color slides, 8mm movies, 16 mm movies and videotape. More than 500 still photographs were made and significant findings were then recorded on movie film or videotape. Lighting was provided by two portable 500 watt, tungsten-halogen lamps.

3. Discrete Wing Tip Jet Models

The wing model used in the water tunnel tests was an NACA 0012-64 airfoil section with a semispan of 10.75 inches and a chord of 6.375 inches. The model was made of aluminum and painted white for improved photography. One end of the wing was mounted to a shaft extended through the side wall of the tunnel. Model angle of attack was controlled via the shaft and measured by a geared counter assembly

external to the tunnel. The wing tip jet ports, located at the opposite end of the wing, were at 60 percent of the tunnel width. The wing was located forward in the test section to permit viewing as much of the roll up process as possible. The selected position--12 inches from the front of the test section--insured that the free stream was uniform and parallel ahead of the wing and still permitted visualization of vortex development for approximately 7 chord lengths downstream of the wing trailing edge.

The model was designed such that interchangeable tips could be used to vary blowing configuration. The tip configurations selected for water tunnel testing were chosen in order to assess the influence of changes in jet sweep angle, jet dihedral angle, and jet shape. It would be a very lengthy process to test all the desired combinations of these parameters. Rather a baseline design was chosen and tested and each subsequent configuration changed a single element of the baseline design in order to determine the isolated influence of that element. The horizontal slit jet port was selected as the baseline design so as to achieve some of the known benefits of wing tip jet sheets and still be able to produce counterrotating vortices. The variations from baseline were sometimes quite large in order to create a flow field sufficiently different that the differences could be easily observed. It is recognized that this method will not identify an optimum configuration since it may fail to produce flow phenomena that occur due to combinations of sweep angle, dihedral angle, and jet shape. Also, the influence of these individual parameters is not

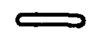
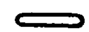
determined exhaustively in that all sweep angles, jet shapes, etc. have not been tested. However, the configuration tested should give qualitative assessments of the relative influence of each of these critical design factors and give direction to further testing.

The tip configurations tested in the water tunnel are listed in Table 1, and two uninstalled wing tips are shown in Figure 6. Individual water supply tubes ran to each jet port through the wing model. The flow rate for each jet was controlled by valves external to the tunnel and measured by a flow meter. One additional configuration tested was a cylindrical extension at the wing tip. The use of that model will be discussed in Chapter V.

Two independent dye systems were used to make the flow field visible. The primary system was the use of dye emitted from the surface of the wing model. This dye followed the roll up of the wing tip vortex and made the undisturbed vortex visible for the entire length of the test section. The dye was a mixture of milk, alcohol and commercial food coloring. Typically, red, green, and blue dyes were used. This dye could also be injected upstream or downstream of the model through several moveable dye probes. Care was taken to insure that a specific gravity of unity was achieved. The dye injection system consisted of pressurized dye reservoirs which supplied the dye to the model through 0.067 inch diameter tubes. Dye flow rate was adjusted by control of the pressure in a manifold connected to each dye reservoir. Dye flow rate was carefully controlled to insure that the dye velocity as it left the model did not produce its own jet effect. The low dye velocities also insured

TABLE 1

WATER TUNNEL JET CONFIGURATIONS

Configuration Designation	Configuration Design Parameter	Sweep Angles*			Dihedral Angles**			Jet Shape
		δ_{j_1}	δ_{j_2}	δ_{j_3}	λ_1	λ_2	λ_3	
I	Baseline	135°	90°	45°	0°	0°	0°	
II	Sweep Angle	150°	90°	60°	0°	0°	0°	
III	Dihedral	135°	90°	45°	-30°	0°	30°	
IV	Jet Shape	135°	90°	45°	0°	0°	0°	

*Sweep angle as defined in Figure 3, page 35.

**Dihedral angle positive for upward blowing.

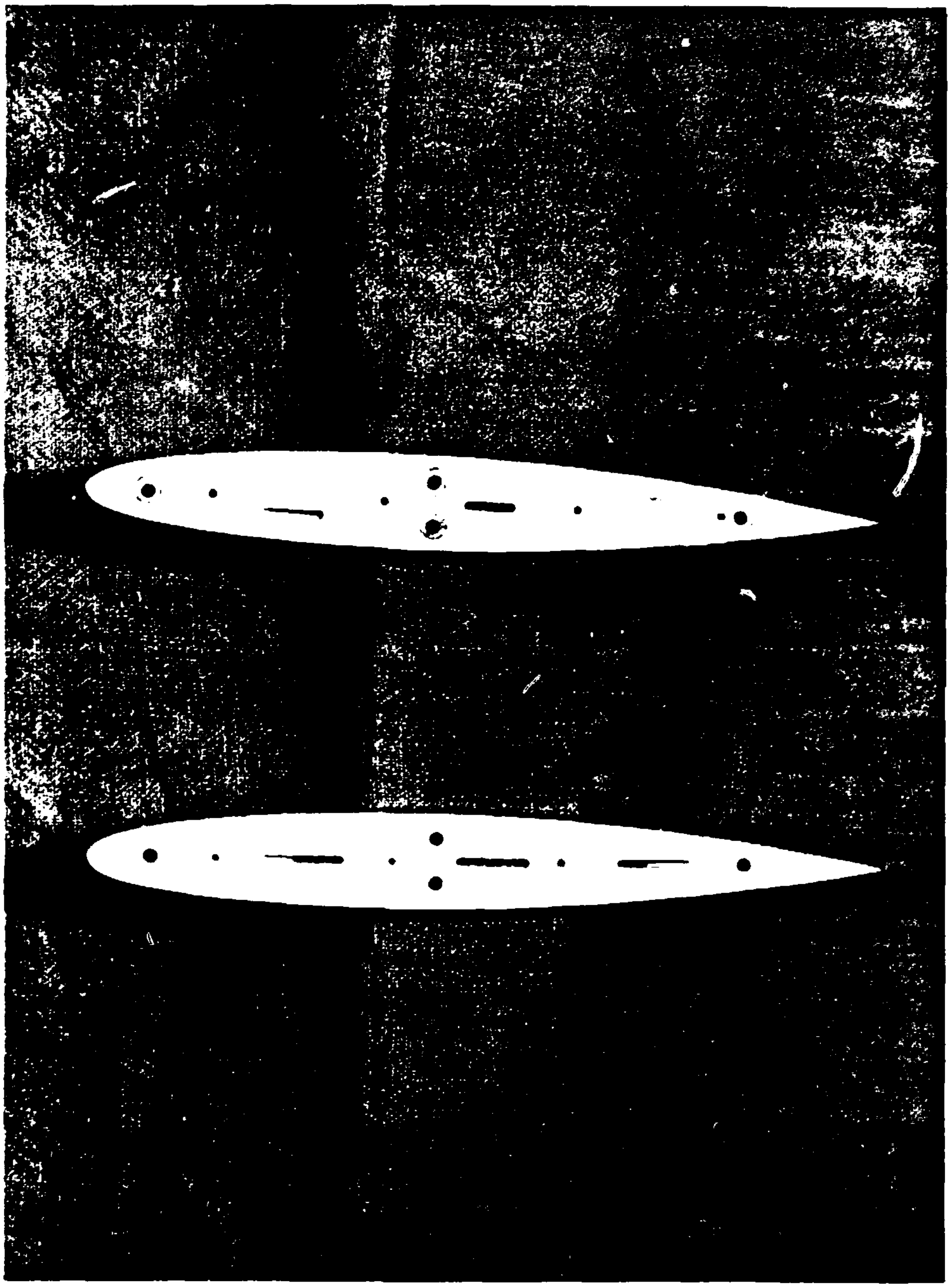


Figure 6. Wing Tip Models II and III

that the dye itself did not become unstable or transition to a turbulent stream. This was important to insure that the streakline traced by the dye was turbulent or unsteady only if the flow itself was turbulent or unsteady.

The secondary dye system was the coloring of the jet fluid itself in order to make the jet visible. This dye was created by inserting a chamber of potassium permanganate ($KMnO_4$) crystals into the water supply tubes which led to the jet ports. Each chamber was located between the flow meter for that line and the feed-through manifold on the tunnel sidewall. The potassium permanganate was readily dissolved by the water flowing through the chamber and created an intense purple dye. This dye was so intense that it originally obscured, rather than revealed, the flow patterns in the tunnel. By use of a bypass system that diverted a controlled amount of water around the potassium permanganate the intensity of the dye could be satisfactorily adjusted. The dye created by this method did not have a specific gravity of unity and was, in fact, observed to sink very slowly when injected into stagnant water. This was not considered to be a significant problem in interpreting the observed flow field.

4. Wall Interference

A major concern in this test was the interaction of the jet with the water tunnel walls. To assess this problem, the method of Fearn and Weston (63) was used to compute the undisturbed path of the jet centerline. For higher values of jet coefficient ($C_\mu > 0.05$) the

undisturbed jet was predicted to strike the tunnel side wall within the test section region. This was investigated experimentally by placing the wing at zero angle of attack and the dye in the jet itself to see if the undisturbed jet approached the side wall. At $C_\mu = 0.05$ the jet was approximately 2 inches from the wall as it left the test section. It is expected that this deviation from a prediction based on well established data is attributable to wall interference. Indeed, at extremely large jet coefficients, outside the data range of the experiment ($C_\mu > 0.5$), wall interference was obviously present since the actual impingement of the jet on the wall could be seen. However, it is very important to remember that these observations as well as the theoretical prediction mentioned above are for an undisturbed jet. In particular, the influence of a strong vortex near the origin of the jet and running parallel to its path is not included. Observations in the water tunnel clearly showed that when the wing assumed a nonzero angle of attack and began producing lift, the jet trajectory was invariably pulled back toward the wing and away from the wall. The data presented in Chapter V shows this very graphically. Obviously the effect of the wing tip vortex is to greatly reduce the potential for wall interference. Thus two criteria prove to be important in minimizing wall interference: realistic jet coefficients ($C_\mu < 0.3$) and the production of lift (especially for $C_\mu > 0.05$). Within these limitations the influence of the wall is of negligible importance with respect to the interactions between wing tip jets and wing tip vortices.

CHAPTER V

RESULTS OF THE INVESTIGATION

Discrete wing tip jets proved to be very effective in dispersing the coherent structure of the wing tip vortex. Figure 7 shows the wing tip vortex for an angle of attack of 12 degrees and no wing tip blowing. The vortex was easily visualized and was found to be very stable, very persistent, tightly rolled and quite strong. Rotational velocity appeared to be of the same order of magnitude as free stream velocity and decreased only slightly within the test section region. There was little or no diffusion of the vortex to the surrounding fluid and minimal mixing of the dye traces within the vortex core. In contrast, the flow field produced by the introduction of jet blowing, which is shown in Figure 8, had a completely different character. The dispersed and somewhat unsteady vortex, as identified by the dye, was much larger in diameter and the core of the vortex (i.e., the axis about which rotation occurred) was not identifiable. In fact, rotational motion, if present, was difficult to detect due to the mixing which occurred and the diffusion of the dye streaks. Figure 9 is a top view of the flow field when the jets have been cycled on and off. The contrast in vortex structure is very striking; actual observations were even more so in that no rotation was seen in the region where the jet was operating. The dye trace from the probe placed near the trailing edge of the wing was completely entrapped and

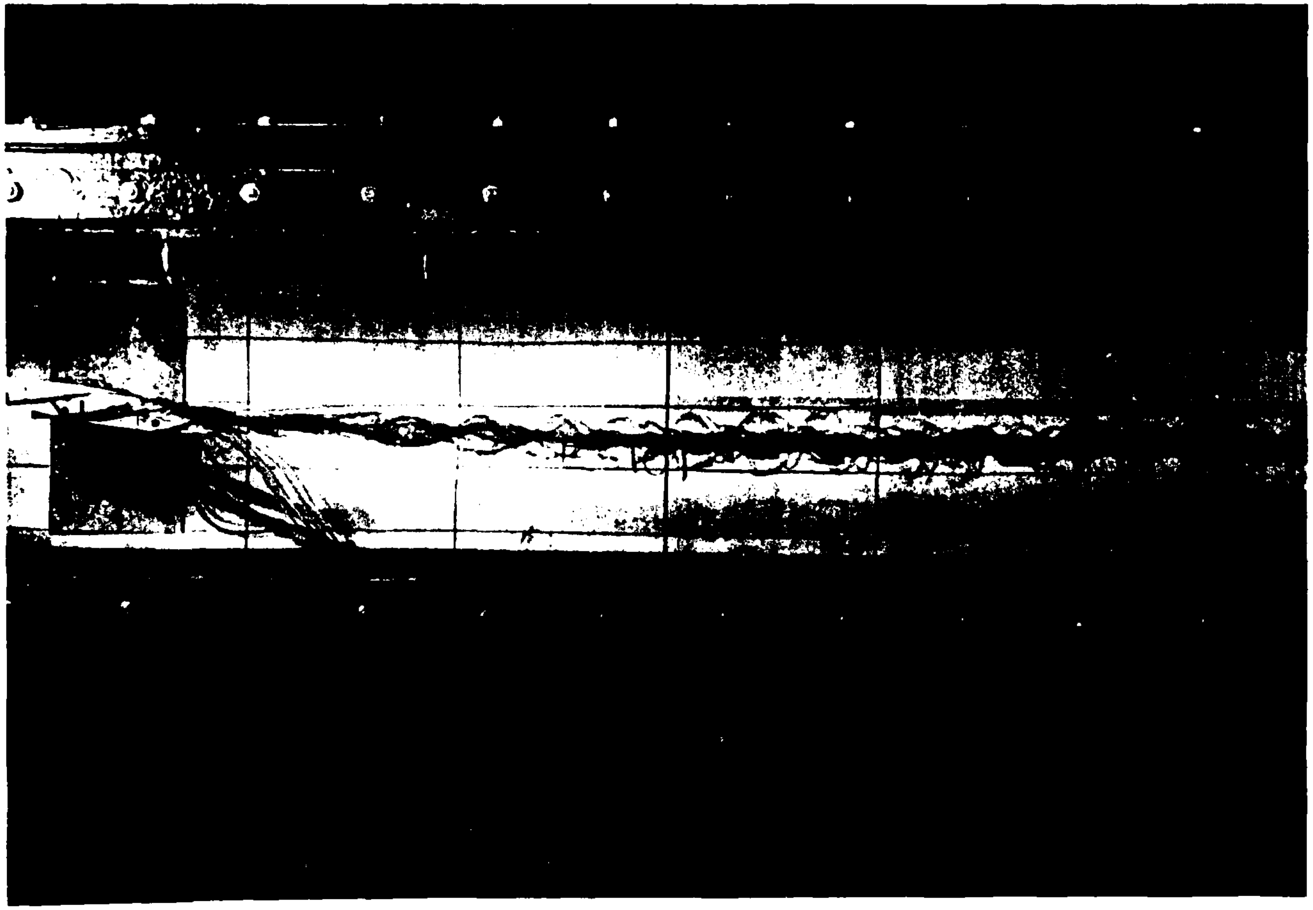


Figure 7. Wing Tip Vortex, No Blowing

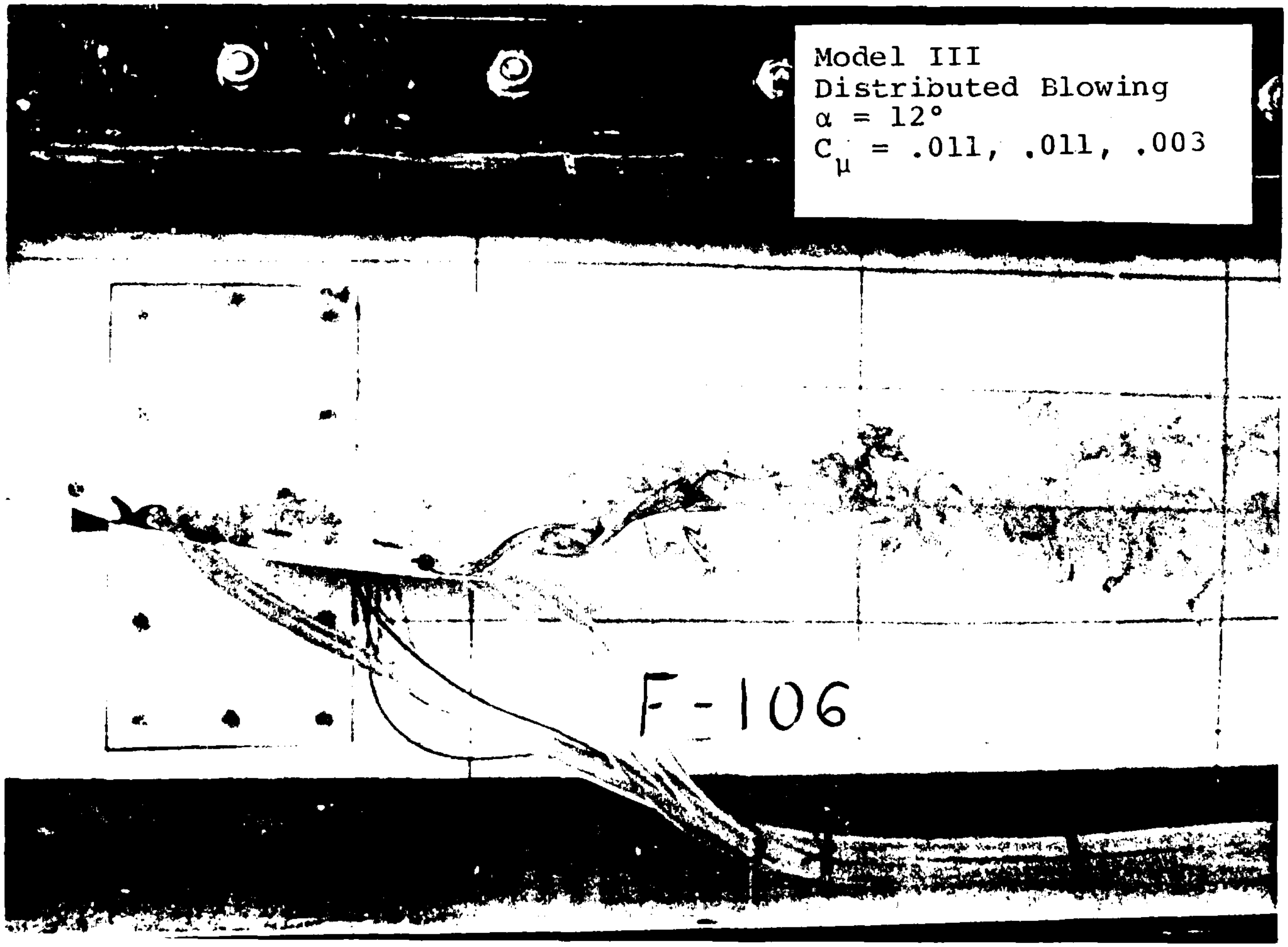


Figure 8. Dispersed Wing Tip Vortex

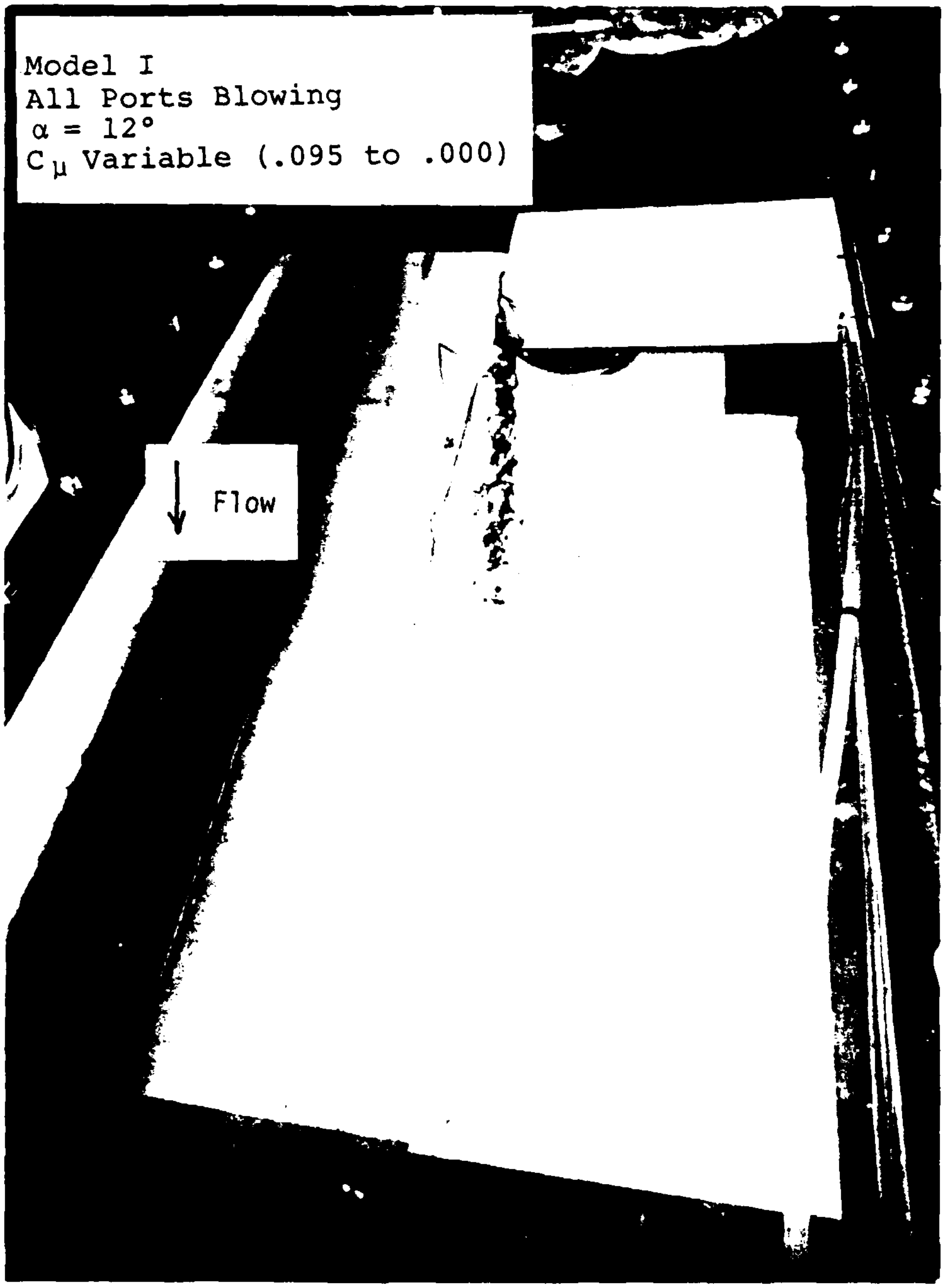


Figure 9. Dispersed Wing Tip Vortex, Top View

mixed with the remains of the vortex when the jet was on, but separated from it immediately when the jet was turned off. This indicates that the jet blowing substantially enlarged the diameter of the vortex. In summary, the jet blowing caused a significant breakdown of the observable structure of the wing tip vortex.

The degree of vortex dispersion depended on both jet configuration and jet coefficient. These influences will be discussed in the last section of this chapter. However, to properly introduce that discussion, several unusual and interesting phenomena that were observed during the study will first be presented. An awareness of these isolated phenomena and some understanding of their influence is prerequisite to understanding the very complex structure and interactions of the jet-vortex flow field.

1. Influence of Counterrotating Vortex Pair

The two counterrotating vortices characteristic of a jet in a cross flow were clearly seen in the water tunnel tests. Figure 10 shows the two vortices as two distinct lines in the jet itself. This photograph shows the flow pattern for a single jet from the aft port of the baseline configuration at $\alpha = 0°$. Observation of the flow confirmed that the two vortices rotated in opposite directions. These "jet vortices" developed very quickly after the jet left its orifice. Their rotation was easily discernible although rotational speed was low at low jet coefficients such as in Figure 10. When two or three jets were used, there would be multiple pairs of counterrotating vortices.

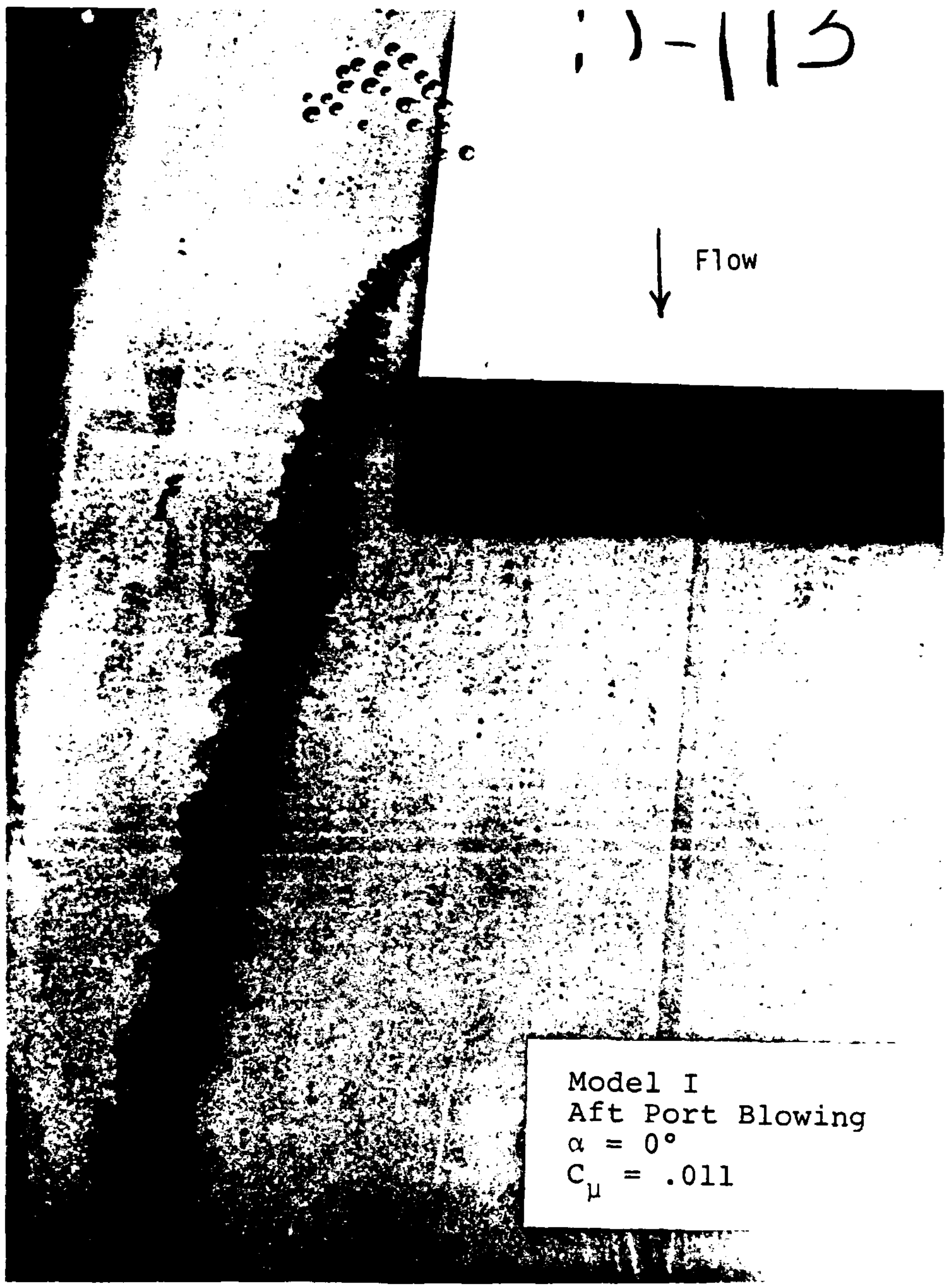
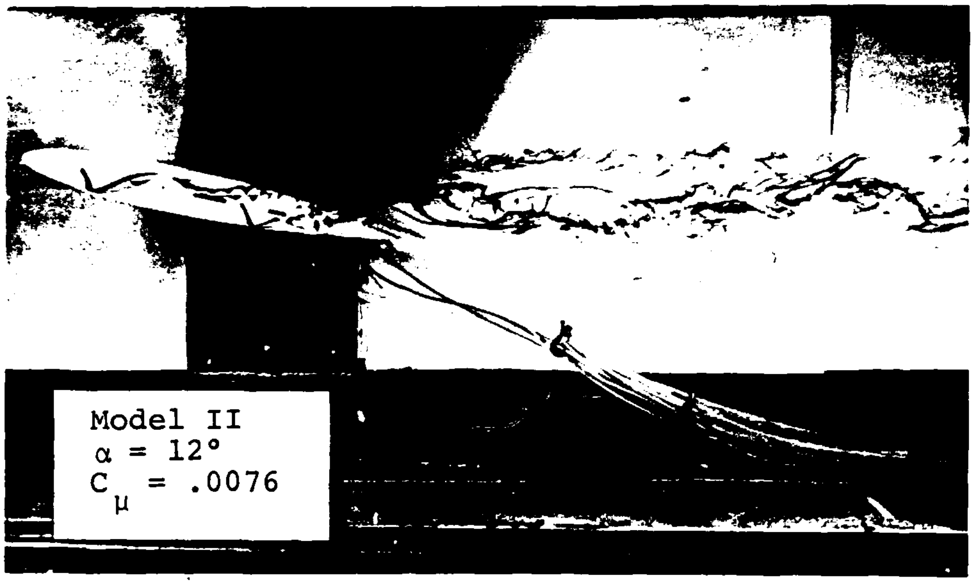
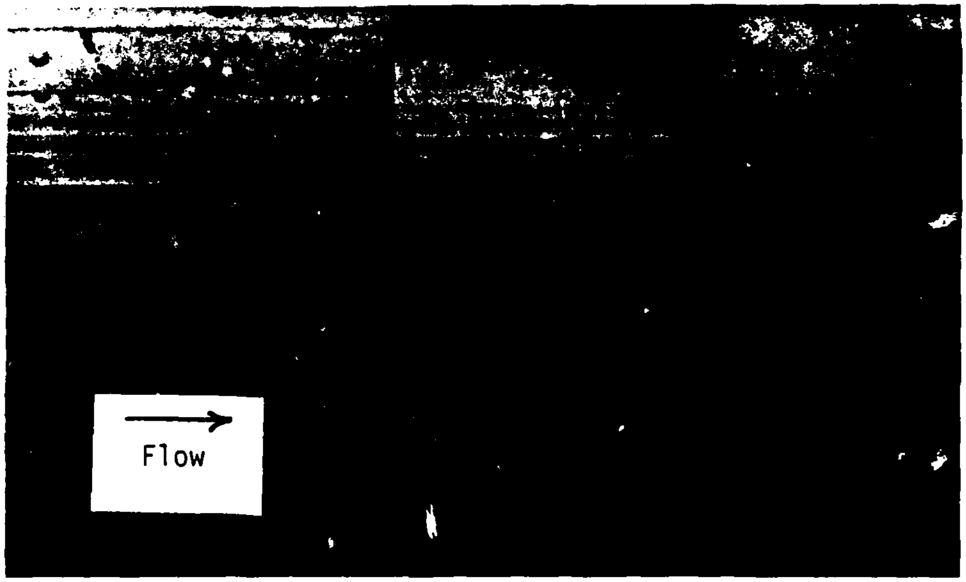


Figure 10. Counterrotating Vortex Pair

When the wing was placed at positive angle of attack, the counterrotating vortex pair would be lifted in the negative z direction (see Figure 1, page 5) and wrapped around the wing tip vortex. Figure 11 shows this clearly. This is model II, the nonstandard jet sweep model at 12 degrees angle of attack with blowing through the aft port only. Actually, only one of the counterrotating pair (the one rotating opposite to the wing tip vortex) is visible. This was the usual case although both members of the pair were occasionally seen for lifting wings. There are three explanations why one vortex was often missing. It is quite likely that the pair of counterrotating vortices are not equal in strength as in the symmetrical, $\alpha = 0°$, case. At lifting conditions, the flow around the tip causes the cross flow to be nonuniform, and the jet sheet leaves the jet port at an angle of incidence with respect to the local flow. Thus, the cross section of the jet is likely to be asymmetric as well as the strengths of the vortices embedded in the jet. It is also possible that the jet vortex rotating similarly to the wing vortex was pulled into the wing vortex system very near their origins. The flow near the jet orifices was too complex to state this with certainty, but some indications of jet vortex entrainment into the wing vortex system were seen. The likelihood of this happening is also addressed by the computational model in Chapter VI. Thirdly, the invisible member of the counterrotating pair may have been present and parallel to its partner but not seen because it had captured no dye. Figure 11 and most of the other photographs were made using the primary dye system from surface dye ports. The jet vortices and all other flow



a. Side View



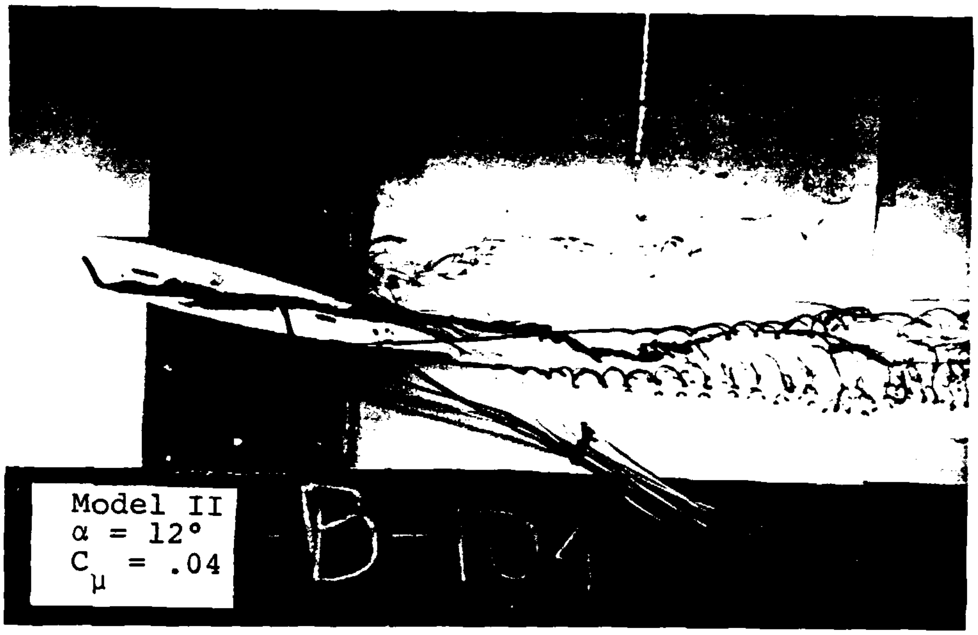
b. Top View

Figure 11. Jet Vortex and Tip Vortex, Aft Port Blowing

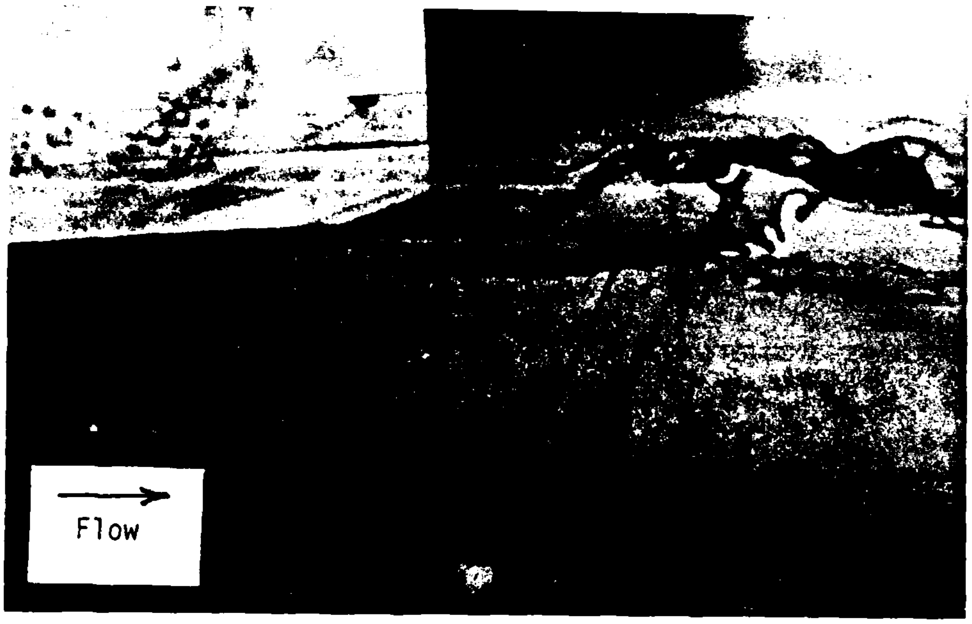
phenomena were visible only when they entrained enough dye to become visible. Experience showed that selecting proper locations for dye ports so that the flow field was made clear was a difficult job. More than once a dye port was closed and another dye port very near the first would be opened revealing a new detail of the flow field . Thus, though the flow patterns seen in Figure 11 and in subsequent pictures are very informative, one must always remember that they are perhaps incomplete. Also, the streamline is visible only where the local flow is laminar; regions of turbulent local flow will diffuse the dye and make streamlines invisible.

The jet vortex seen in Figure 11 was eventually pulled into the wing tip vortex system. This merger was gradual rather than abrupt, but the turbulent mixing appeared to intensify during the merger and downstream from it. The production of the jet vortices create a flow field comparable to the one produced by a deflected flap or a wing fin as discussed in Chapter II. The occurrence of the jet vortices and the favorable influence that they have on dispersion of the wake vortices remind one of Ciffone's guidance (28) that alleviation is attained by causing wake vortices to interact and merge.

An interesting change occurs in the trajectory of the counterrotating vortex when the front jet port is used. Figure 12 shows the flow field for front port blowing from model II at α = 12°. As can be seen, the separation--both horizontal and vertical--between the counterrotating vortex and the wing tip vortex was significantly greater than was seen in Figure 11 for aft port blowing. The counterrotating vortex is visible from a point very early in its



a. Side View

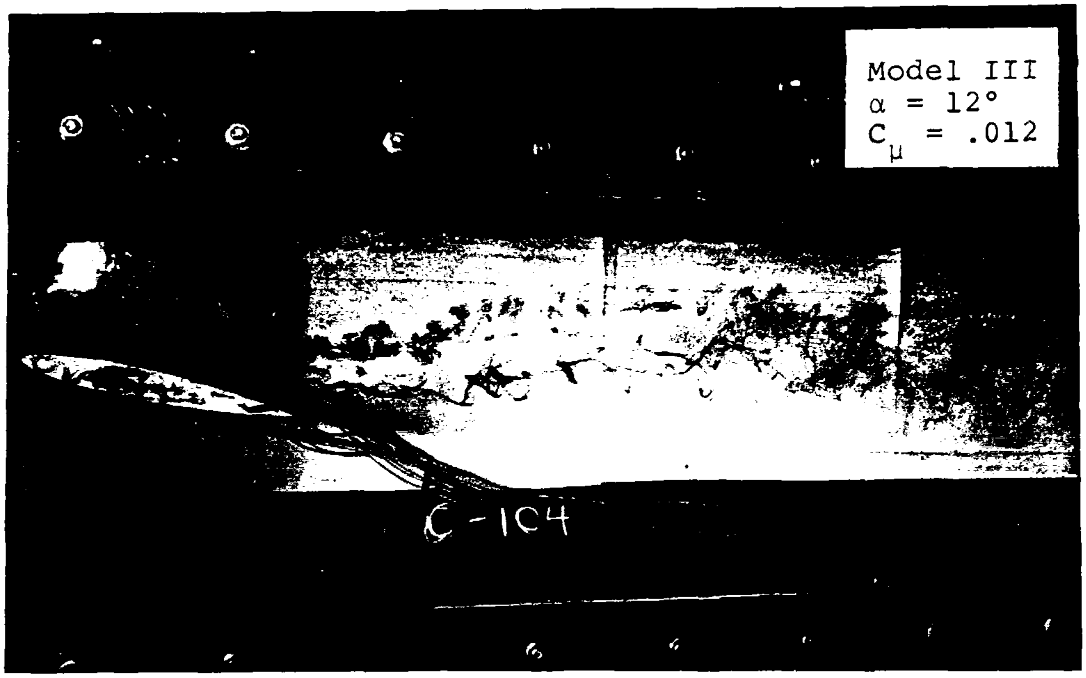


b. Top View

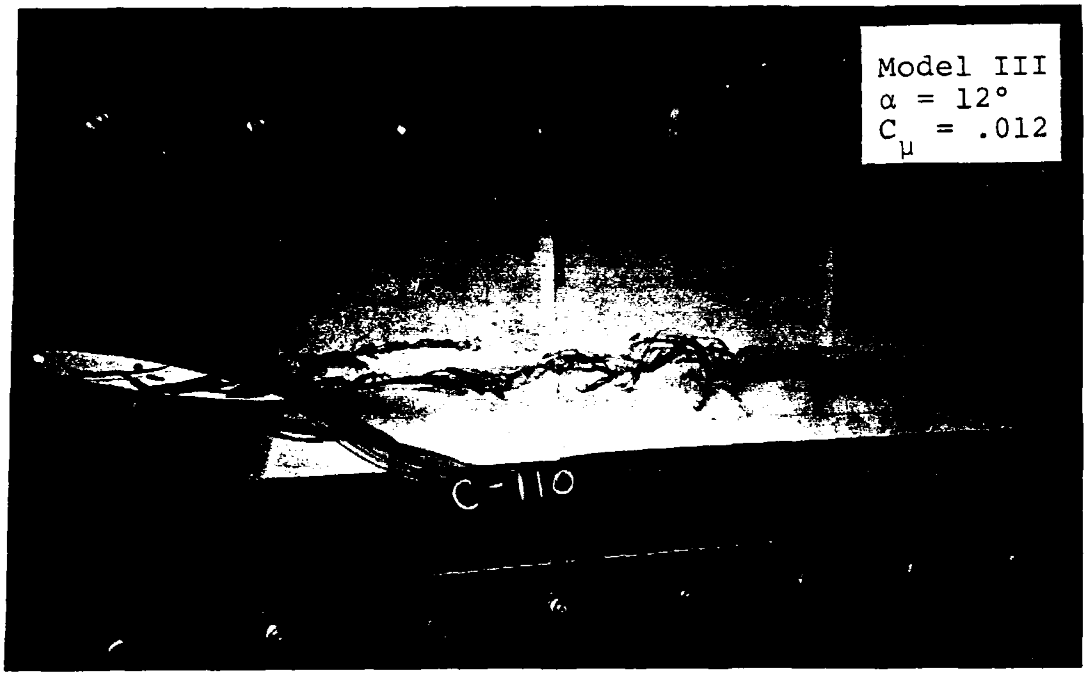
Figure 12. Jet Vortex and Tip Vortex, Front Port Blowing

development and is seen to move outboard and toward the suction side of the wing rather than becoming involved in the development of the wing tip vortex. This initial movement establishes a trajectory which results in the increased spacing seen in the wake. It is believed that this increased spacing will retard, or at least delay, the interacting and merging process which produces vortex dispersion. It should be added that front port blowing caused noticeably more unsteadiness than did other ports. It is believed that the pictures show the usual trajectories of the jet and wing tip vortices , but some variation from the usual positions (particularly for front port blowing) was often observed. As an incidental note, Figure 12 also shows how the dye was affected when the milk and alcohol began to coagulate and form particles. This would occur at the end of a long run or when the test was interrupted tc fix a problem (such as the leak in Figure 12).

Similar flow patterns were seen in tests with other jet configurations. In particular, model III showed similar vortex trajectory patterns when forward and aft jet blowing were contrasted. This occurred even though the influence of the nonzero dihedral on model III was to create initial jet velocities such as to decrease the spacing for front port blowing and increase the spacing for aft port blowing. Figure 13 shows that the spacing patterns were changed very little by the jet dihedral. Thus, jet location (or perhaps forward versus reverse sweep) is the more important factor in determining counterrotating vortex trajectory.



a. Front Port Blowing



b. Aft Port Blowing

Figure 13. Vortex Trajectories for Model III

The counterrotating vortices were seen only at low jet coefficients, as shown in the previous figures, where turbulent mixing was low. However, the vortices are certainly present at higher jet coefficients and their influence on the wing tip vortex should be even greater.

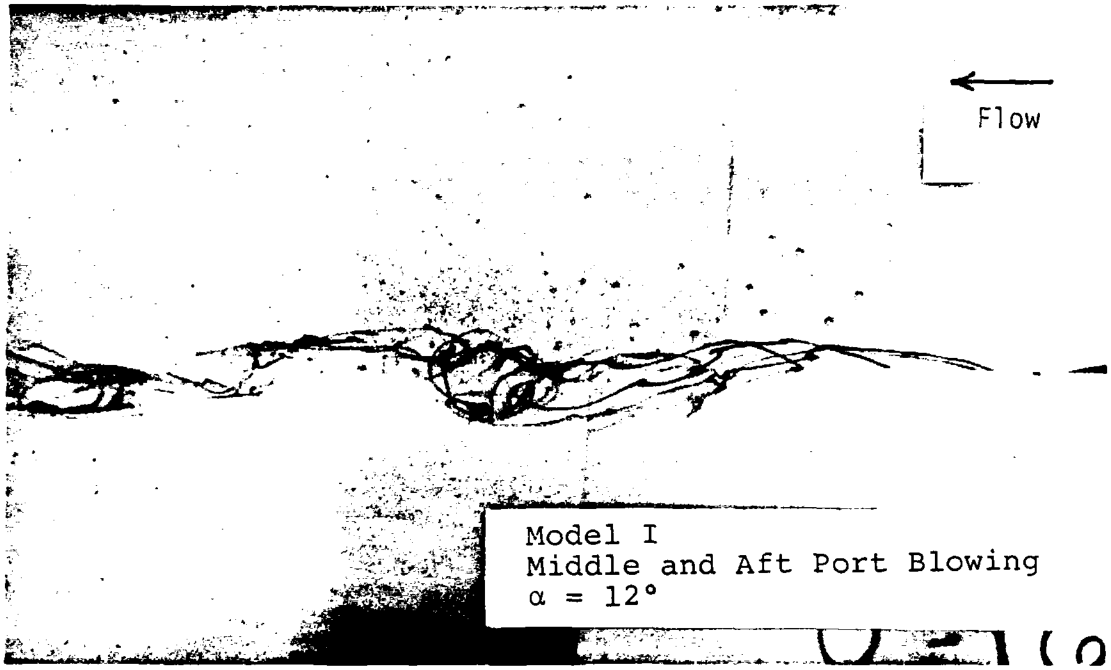
2. Trajectory of the Wing Tip Vortex

Jet blowing had two distinct effects on the location where the wing tip vortex originated and its subsequent trajectory.

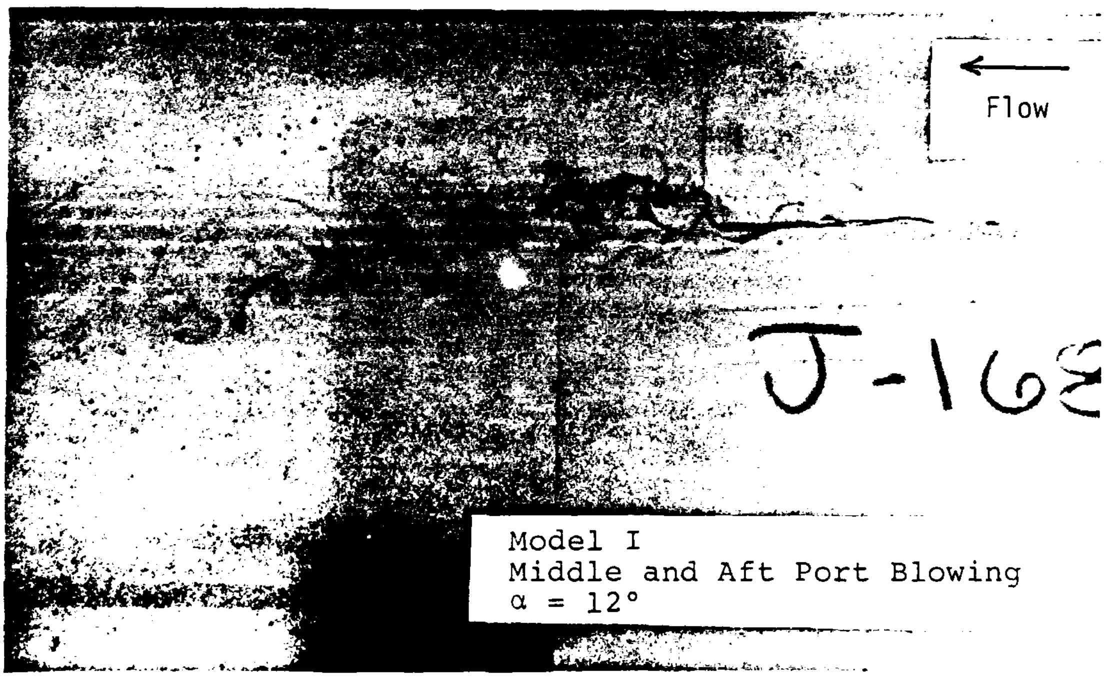
Effective Increase in Aspect Ratio

Discrete wing tip jets have demonstrated the capability to increase lift on a wing (1,2), and this improvement in lift efficiency is expected to provide significant reductions in induced drag. Thus, the effect of the jets on wing aerodynamics is very similar to a physical extension of the wing or an effective increase in wing aspect ratio. One goal of the water tunnel experiment was to visualize this process, and, if possible, develcp guidelines for maximizing the improvement.

It was found that jet blowing did shift the wing tip vortex outboard even for small amounts of blowing. Figure 14 compares vortex position as a function of jet coefficient for the baseline model at $\alpha = 12°$ with the middle and aft ports blowing. At $C_\mu = 0.0$, the vortex rolls up over the trailing edge of the wing tip and obscures it. At $C_\mu = 0.006$, the vortex is shifted outboard noticeably, and the core is actually formed at a point beyond the wing tip. For



a. $C_\mu = 0.000$



b. $C_\mu = 0.006$

Figure 14. Lateral Vortex Displacement

heavier blowing, the dye traces are blown outboard abruptly by the jet before roll up over the tip can occur. This evidence of an "effective increase in aspect ratio" effect is very promising, particularly since there are obvious changes at jet coefficients as low as 0.006.

The middle and aft jet ports used simultaneously were most effective in shifting the tip vortex outboard. Use of the aft port alone was successful in blocking vortex development over the aft part of the wing, but allowed that portion of the vortex which developed over the front part of the wing to continue unimpeded. This is shown in Figure 15 where roll up is occurring over the wing tip even though $C_{\mu} = 0.05$. Independent front port blowing could eventually move the entire vortex outboard but only for fairly high jet coefficients. Figure 16 shows the vortex position for front port blowing with $C_{\mu} = 0.021$. Movement was not found at lower jet coefficients. Also, it was observed that blowing from all three ports was no more effective than blowing from the middle and aft ports. This is probably because the front ports were located forward and blew forward. Hence most of that jet passed in front of the developing vortex rather than intersecting it and extending it outward. The middle and aft ports were located such that their influence on vortex position was far greater.

The photographs used in discussing vortex position were all taken at an angle of attack of 12 degrees. It is recognized that aerodynamic improvements are most important at lower angles of attack which would be typical of cruise flight. It is also recognized that the flow patterns and jet influences seen at $\alpha \approx 12°$ may not be

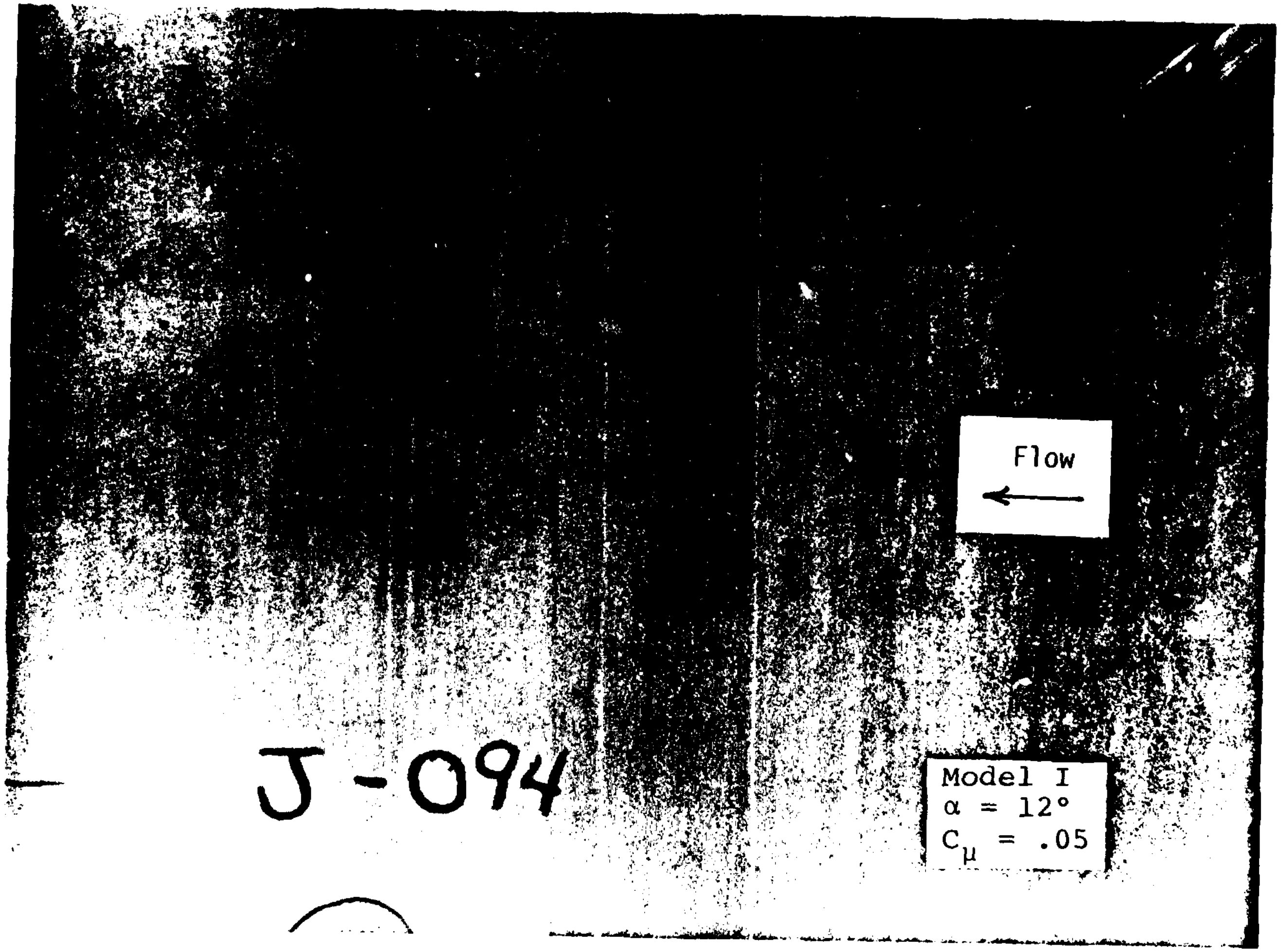


Figure 15. Lateral Vortex Development, Aft Port Blowing

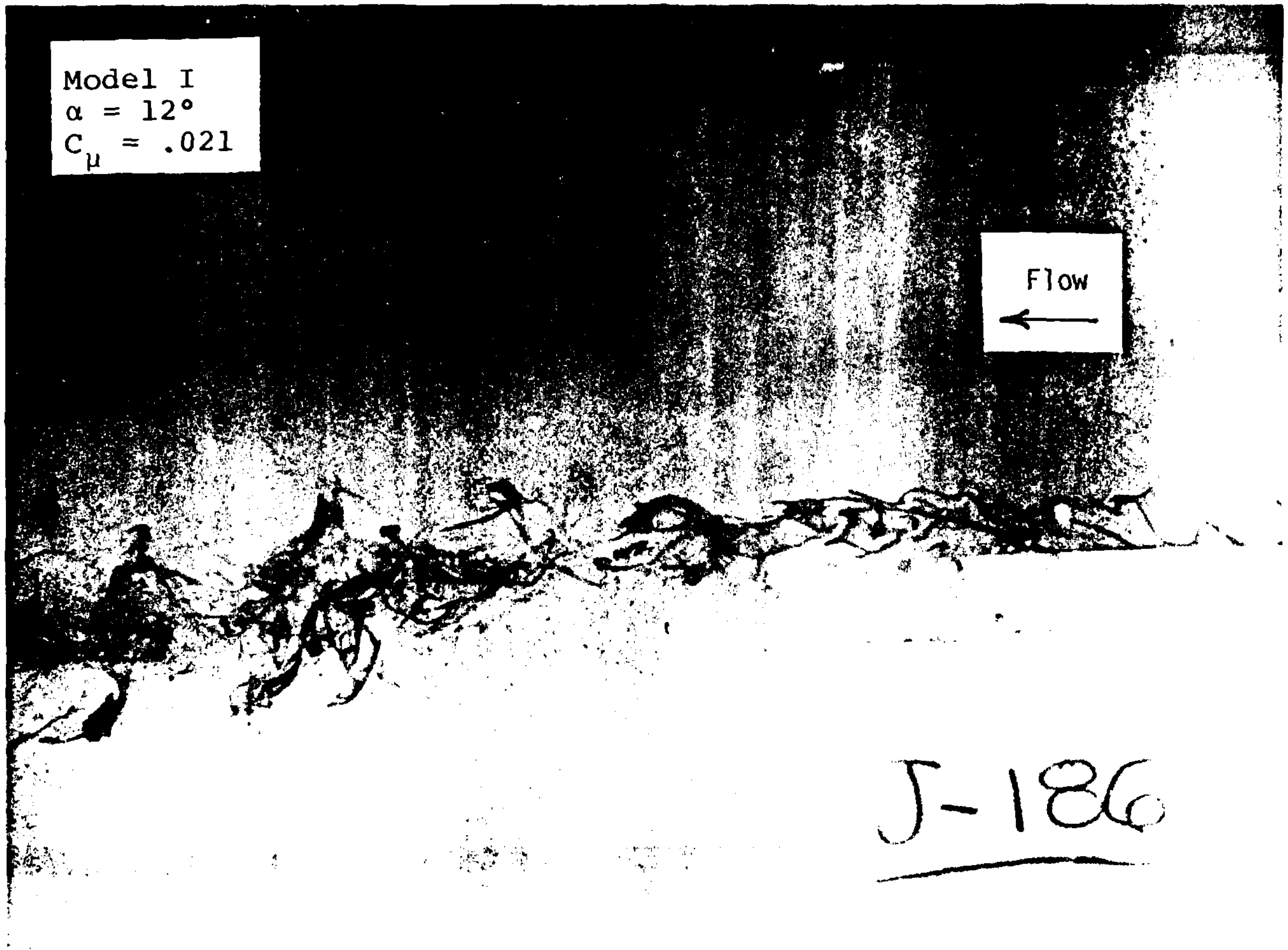
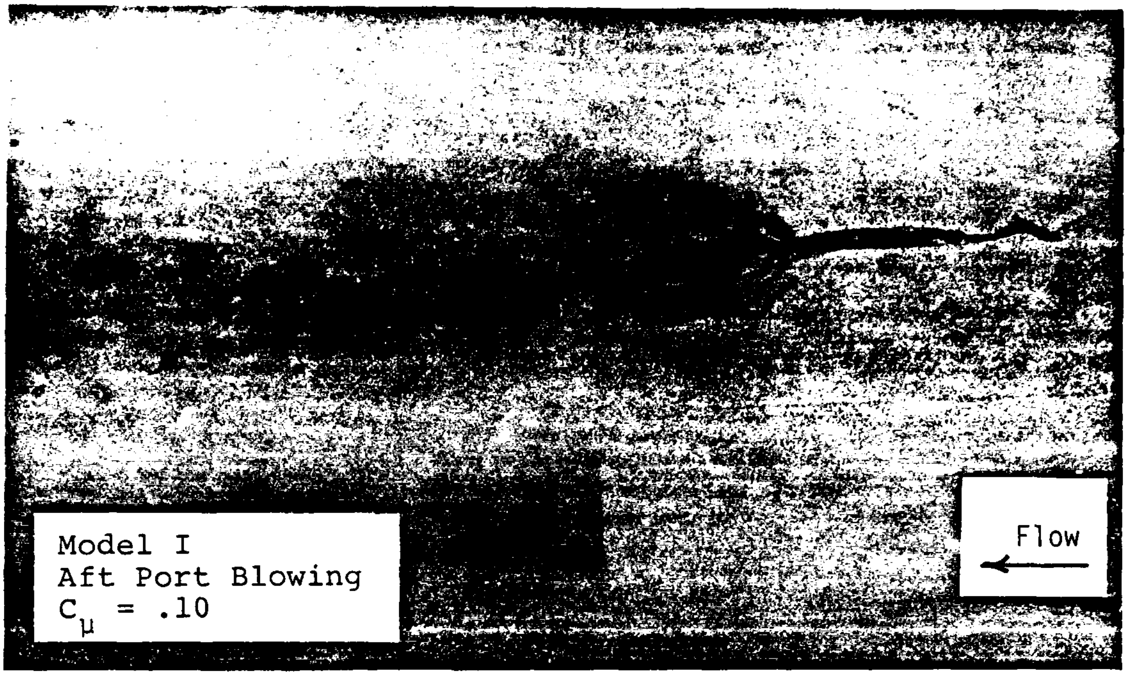


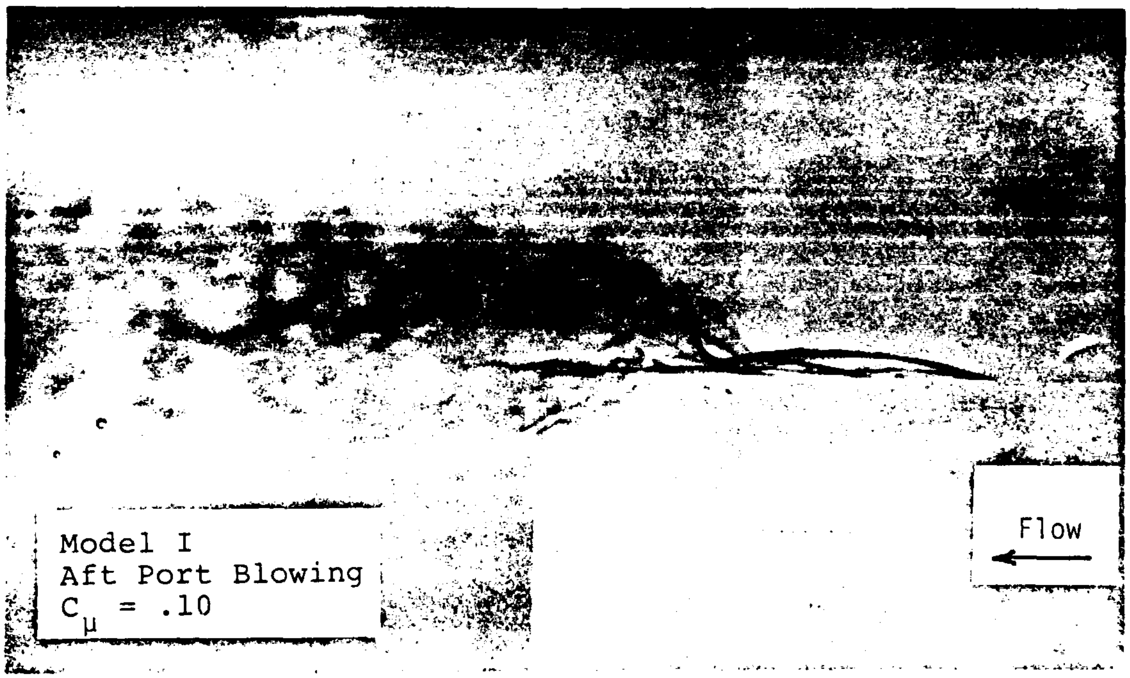
Figure 16. Lateral Vortex Development, Front Port Blowing

repeated at $\alpha = 6°$. However, limited data was taken at lower angles of attack because the primary goal of this experiment was to investigate wake vortex alleviation at angles of attack simulating takeoff or landing operations. Further wind tunnel testing will be needed to quantify aerodynamic improvements. Fortunately though, the limited data did show vortex movement at $\alpha = 6°$, and indicates that the jets might be even more effective at lower angles of attack. Figure 17 shows the flow patterns for two cases with aft port blowing at $C_\mu = 0.10$. In Figure 17b at an angle of attack of 6 degrees, the tip vortex is moved further outboard than in the 12 degree case. This can be seen in the wake and also in the early part of the dye trace which is actually ahead of the jet. This increased effectiveness is not completely unexpected since a jet of constant strength should be more effective against the weaker vortex. However, it is gratifying that the increased effectiveness can clearly be seen.

Another encouraging result of the tests at lower angles of attack was that even very small jet coefficients can cause noticeable differences in vortex position. Figure 18 shows the wing at $\alpha = 6°$ with no blowing. Figure 19 shows the same conditions but the aft port is blowing with $C_\mu = 0.001$. This very small amount of blowing causes the dye to be displaced outboard over a section of the chord much larger than the jet itself. This sensitivity to jet blowing promises the possibility of significant improvement in aerodynamic performance for very low blowing rates.



a. $\alpha = 12°$



b. $\alpha = 6°$

Figure 17. Lateral Vortex Position Variation with Angle of Attack

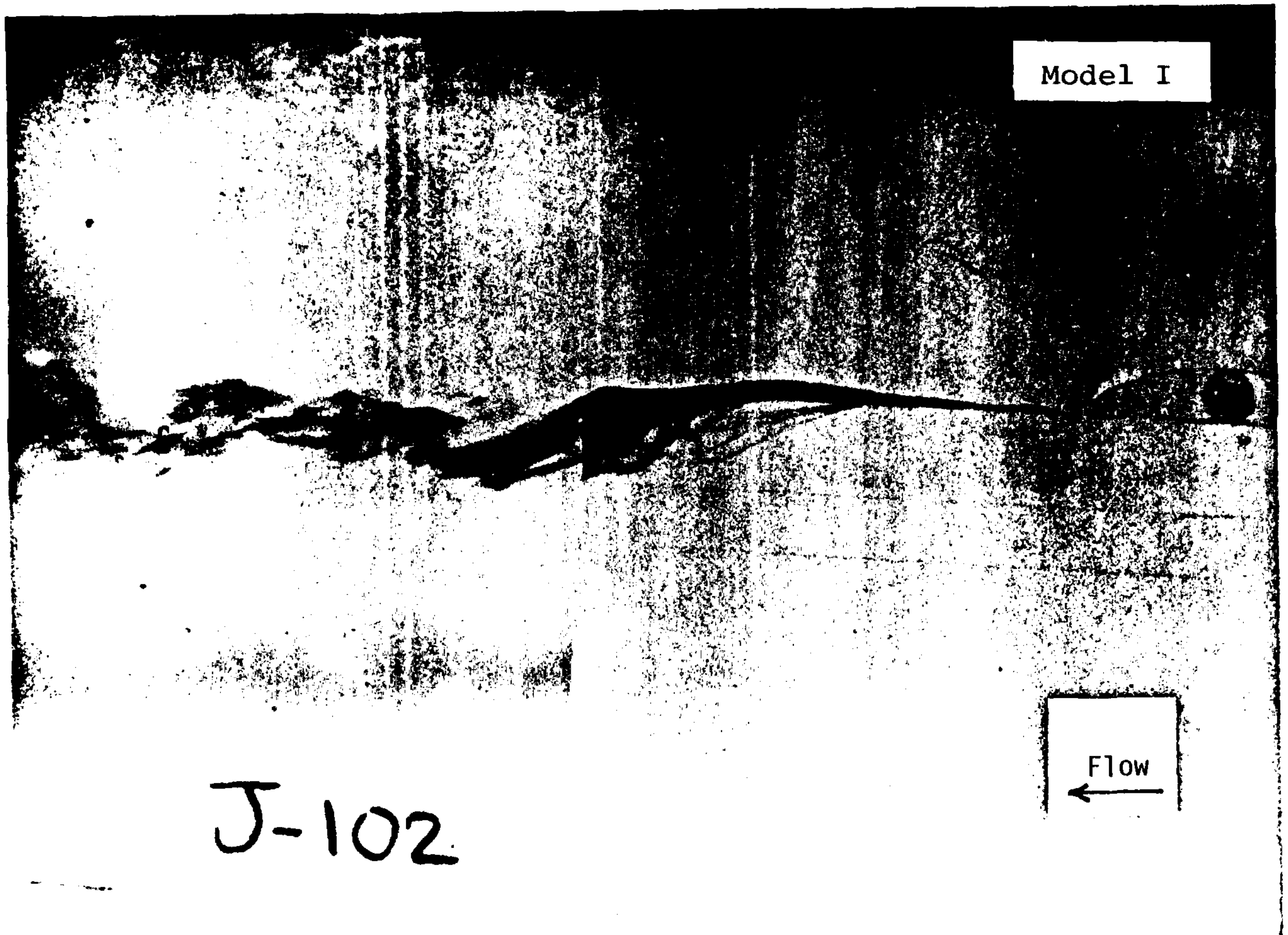


Figure 18. Lateral Vortex Position, $\alpha = 6°$, No Blowing

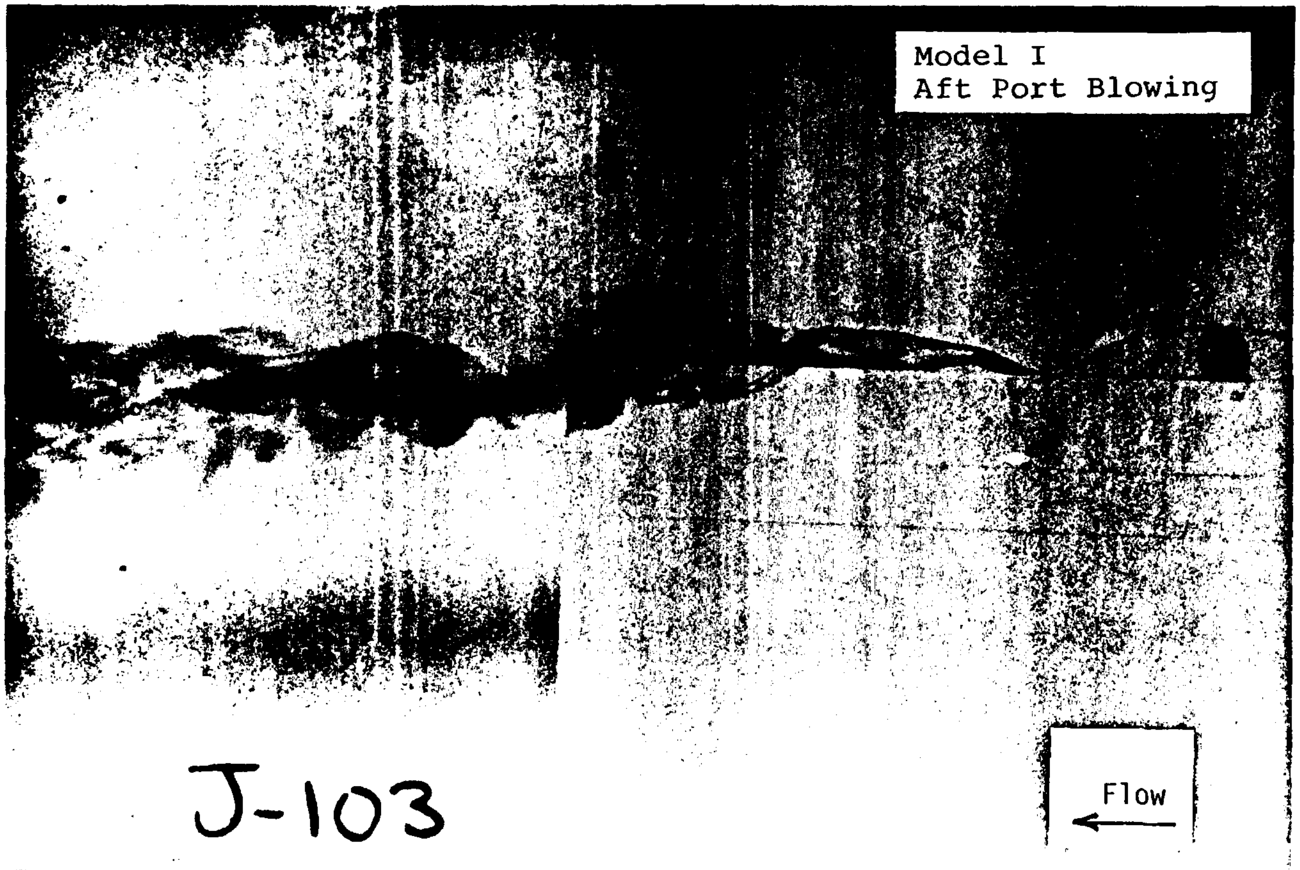


Figure 19. Lateral Vortex Position, $\alpha = 6°$, $C_\mu = 0.001$

Variations in Downwash Characteristics

A significant change in vortex trajectory with respect to its location in a vertical plane was also found. Unlike the outboard shift in the horizontal plane, this result was not expected. Figure 20, when compared to Figure 7 (see page 59), shows a distinct upward shift in the initial vortex trajectory. This shift occurred quite often for a variety of wing tip configurations and blowing conditions. The steepness of the ascent was so great that initially there was concern about dye buoyancy effects. On line checks at $\alpha = 0°$ showed the dye to be neutrally buoyant, and tests at negative angles of attack showed patterns that were quite similar even though dye was then emitted from the suction side of the wing rather than the pressure side. Thus, the upward shift in vortex trajectory is a real effect that may indicate a substantial improvement in wing performance.

The aft jet port seemed to be somewhat more effective than the others in causing the wake vortex to be shifted upwards. Figure 20 shows model III with the rear jet blowing at $C_\mu = 0.071$. This is the wing tip that has the rear jet port at a positive dihedral angle, and the degree of upward motion may be influenced by the dihedral. However, other configurations with no dihedral showed upward vortex movement equally as large. Figure 21 illustrates this for the baseline configuration with rear jet blowing at $C_\mu = 0.050$. The baseline model showed that when aft port blowing was used the upward shift of the wing tip vortex increased steadily with jet coefficient.

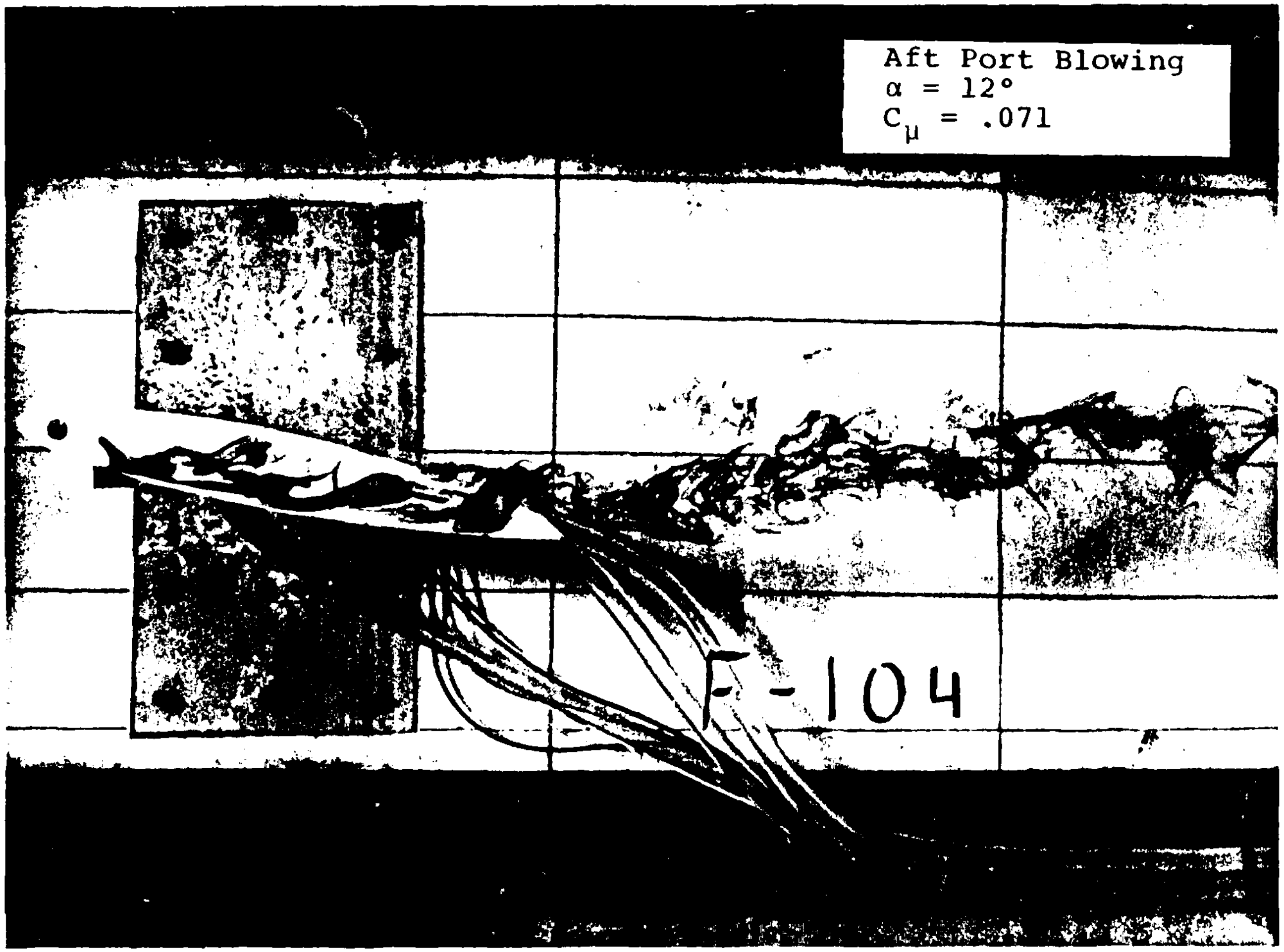


Figure 20. Vertical Vortex Displacement, Model III

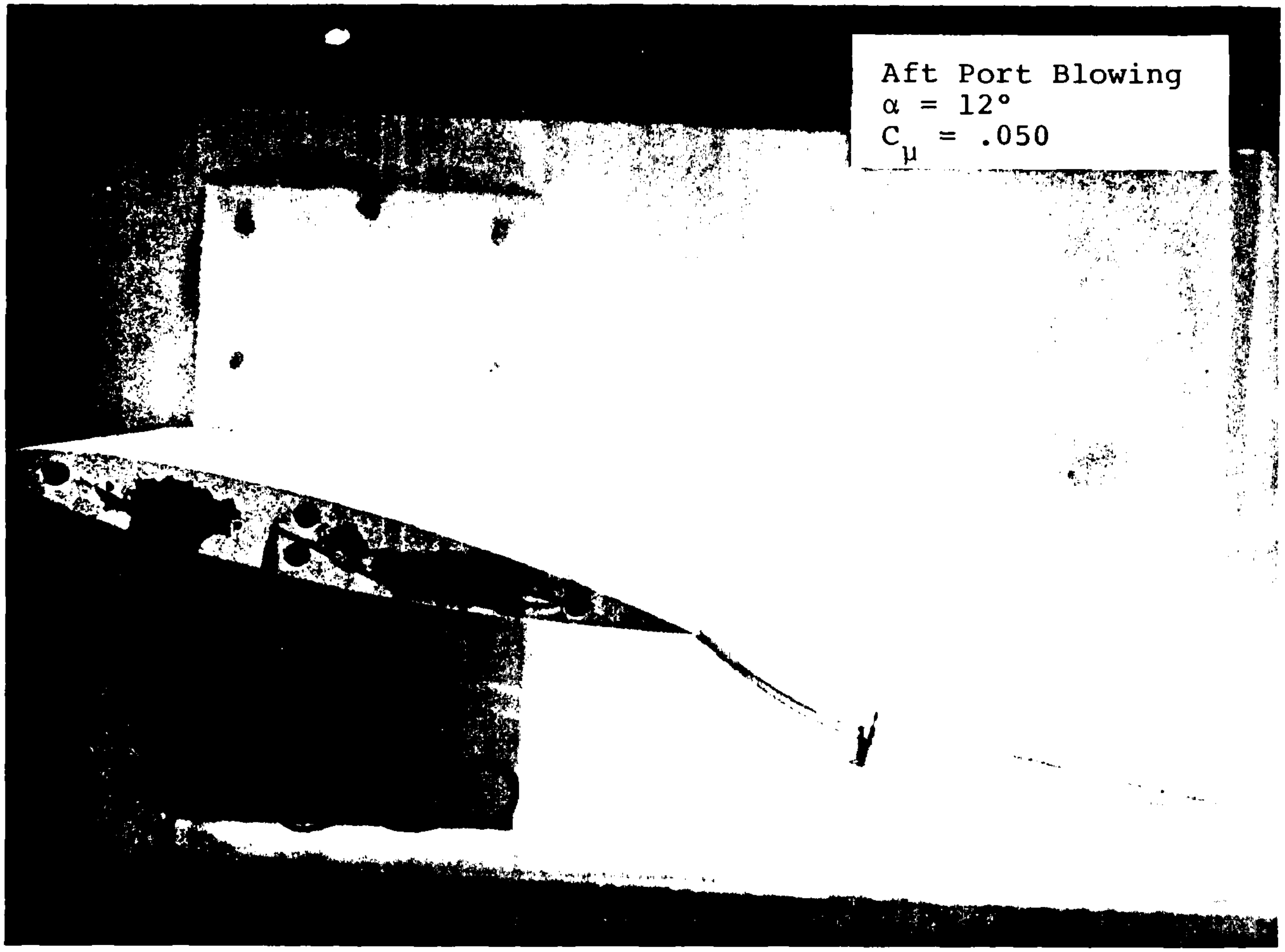


Figure 21. Vertical Vortex Displacement, Model I

However, the greatest changes were seen at jet coefficients of 0.010 and lower. Increases beyond C_μ = 0.010 caused very small changes in trajectory.

Distributed blowing was also effective in causing upward movement of the wake vortex. Figure 8 (see page 60) shows the vortex trajectory for model III with jet coefficients of 0.011, 0.011, and 0.003 respectively front to rear. The upwash is quite strong despite the fact that aft port blowing is light. However, distributed blowing patterns did not appear to be as effective as aft port blowing alone for equal total jet coefficients.

The shift in wake vortex position was sometimes difficult to determine because of the counterrotating vortices produced by the jet. These vortices were sometimes more evident than the wing tip vortex and their dye trace could be interpreted as the tip vortex trajectory. This was especially true for front port blowing where the counterrotating vortex leaves the wing at a very steep angle similar to the vort : trajectories just seen. Figure 13a (see page 69) showed such a vortex path, and the upward shift of the wing tip vortex is now apparent just below the counterrotating vortex. In fact, a comparison of this photograph with Figure 13b (see page 69) would indicate that the front port and not the rear one was more effective at moving the wake vortex upward. Although true here, this was not true at any of several other jet coefficients tested. In fact, front port blowing at jet coefficients greater than 0.012 (as shown in Figure 13a) actually resulted in the vortex being shifted slightly downward from that position. Thus, the analysis of the flow field as influenced by jet

location and jet strength is not at all trivial. The flow field is a tremendously complex one where the strength, trajectory and diffusion of both the wing tip vortex and the vortices imbedded in the jet are mutually interdependent. It should be expected that exceptions will occur in the midst of otherwise systematic results.

The shift in vortex trajectory, and particularly the observation that the vortex remains elevated throughout the observable wake, indicates that the jets may be altering the wing downwash. This "upwash" seen in the wake should likewise influence the flow field ahead of the wing. This influence, if realized, would then cause a reduction in induced drag. Thus, the upwash is another encouraging indication that discrete wing tip jets may result in improved aerodynamic performance.

3. Periodic Secondary Vortices

Description of the Secondary Vortices

The most interesting and unexpected result of the flow visualization tests was the production of periodic secondary vortices in the wake region. In Figure 22 three of these vortices are clearly shown within surrounding turbulence while a fourth is breaking apart. These vortices were formed in a very complex region of flow near the trailing edge. Typically they would emerge from the rolling up tip vortex as a loosely wrapped, swirling dye streak rotating counterclockwise about the y axis (positive y rotation). Each secondary vortex would then be stretched in the positive y direction and would gradually assume a tighter spiraling path as its rotational

AD-A135 872 AN INVESTIGATION OF THE EFFECTS OF DISCRETE WING TIP JETS ON WAKE VORTEX ROLL UP(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH F T GILLIAM AUG 83 2/2

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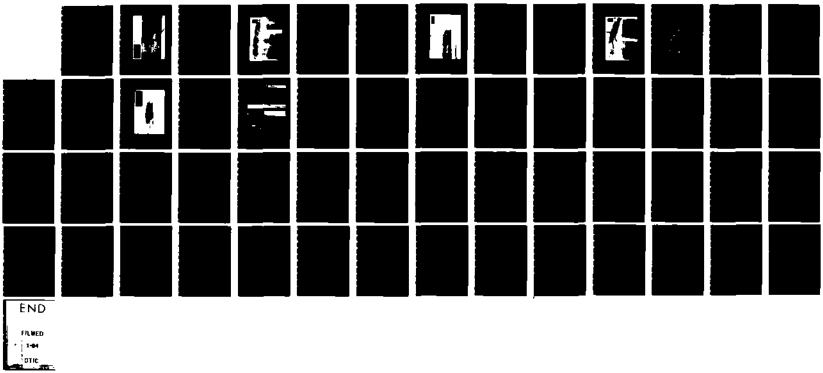

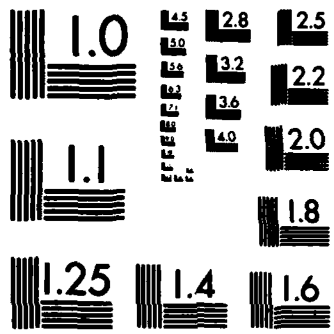

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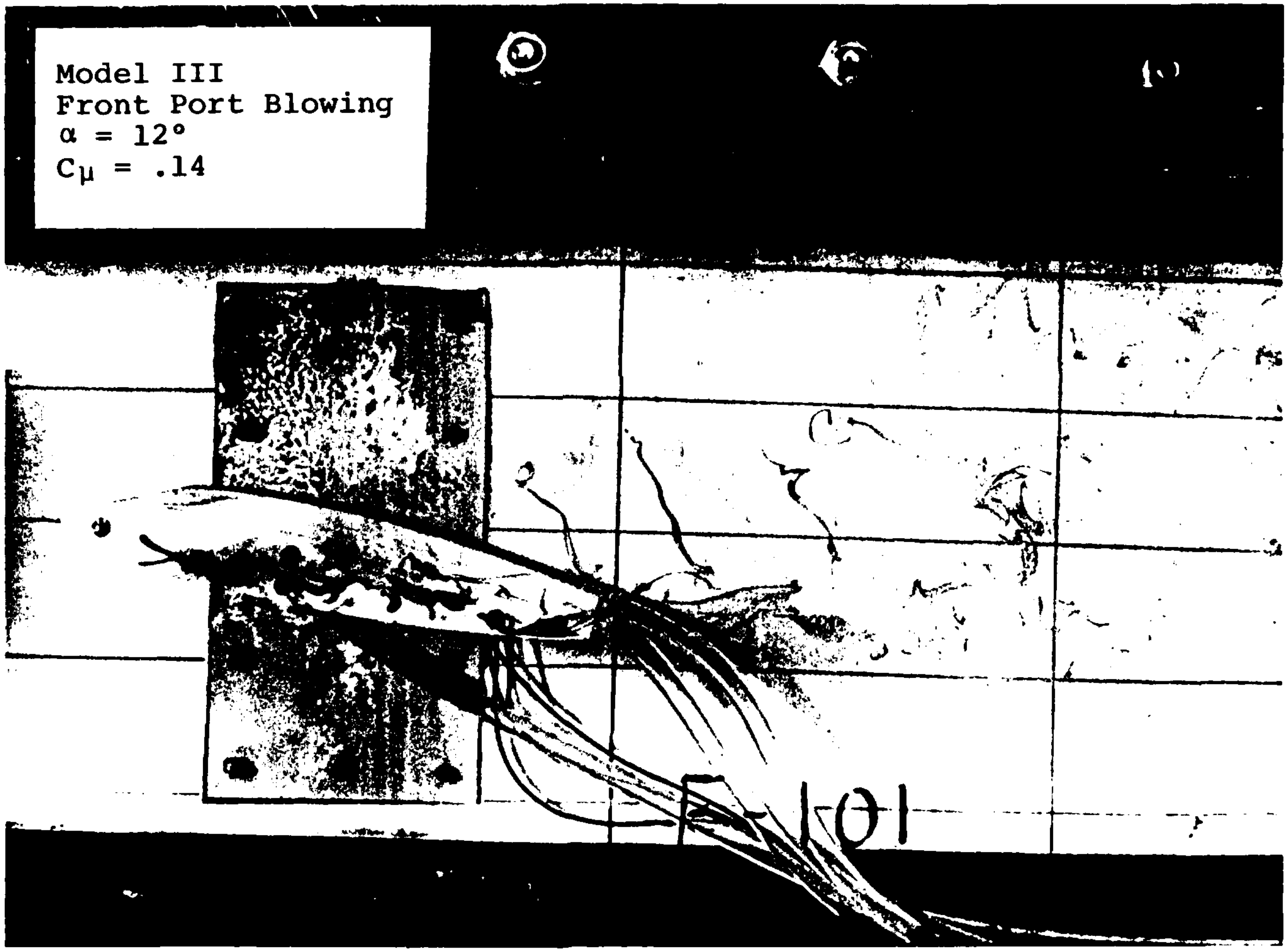


Figure 22. Spin Off Vortices

speed increased. At a point outboard of the wing the secondary vortices would turn quite abruptly so that their path and rotational vector was aligned with the negative z axis. At about this same time the speed at which the tip of the secondary vortex was moving would increase dramatically to a speed that appeared to exceed free stream velocity. The dye marking the tip of the vortex steadily developed a more pointed shape as the vortex was stretched, and the rotational speed of this tip region continued to increase until the streakline abruptly stopped at a position as shown in Figure 22. Because these vortices appeared to emerge from the rolling up wing tip vortex, and because of their rapid spinning, they were called "spin off vortices."

A top view of the spin off vortices is shown in Figure 23. This photograph of the baseline model with front port blowing at $C_\mu = 0.21$ shows one vortex just forming slightly ahead of the trailing edge and three fully developed and regularly spaced vortices.

Causative Jet Characteristics

Periodic spin off vortices occurred when heavy blowing from the front jet port was used. Jet coefficients of approximately 0.16 were most effective at producing distinct periodic secondary vortex patterns. Secondary vortices were never associated with blowing from the middle or aft jet ports. In fact, even small amounts of blowing through the middle or aft ports blocked the development of the spin off vortex system.

A singular secondary vortex identical to the periodic ones was often found to occur when front jet port blowing was initiated. This

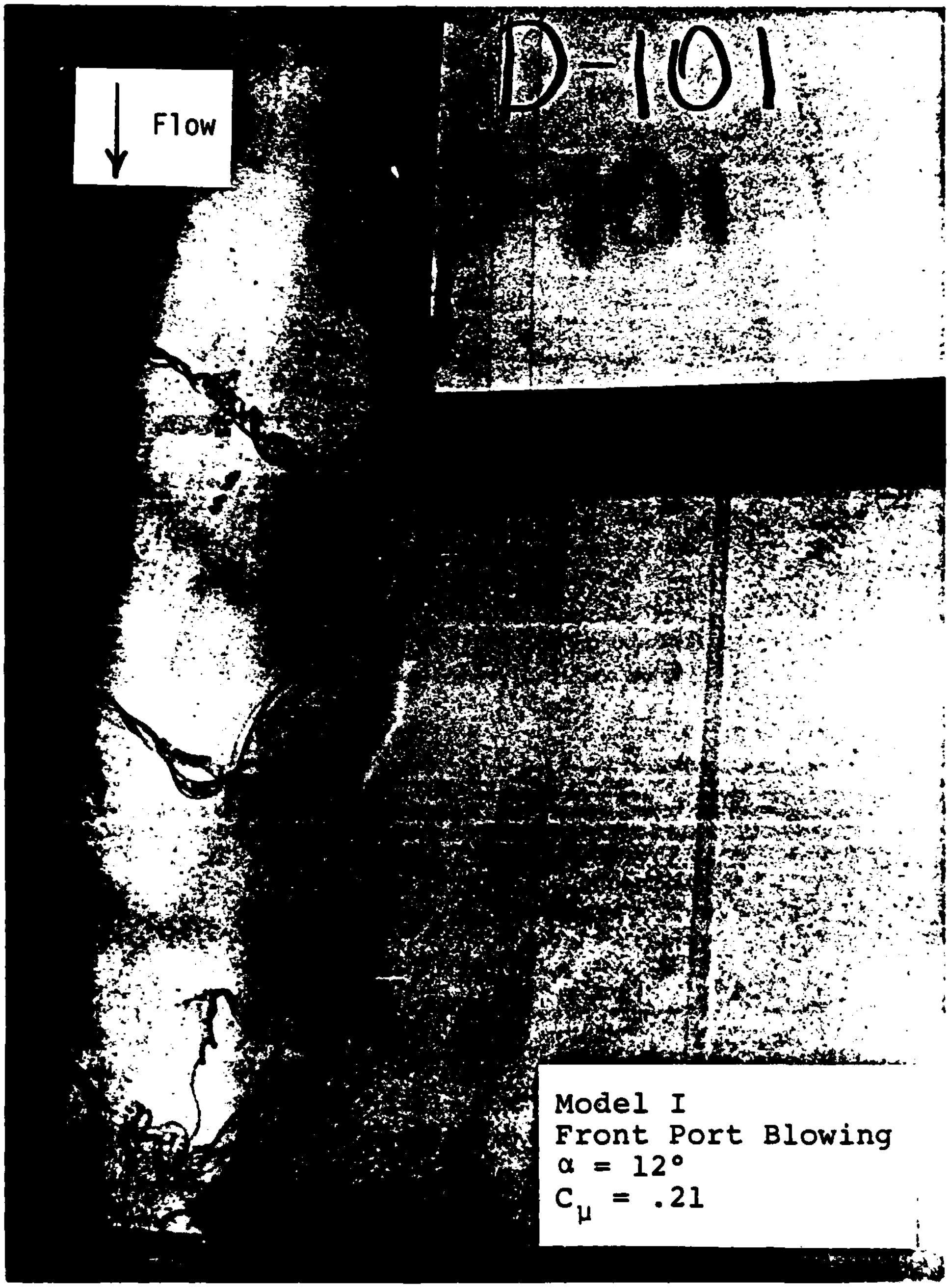


Figure 23. Spin Off Vortices, Top View

vortex occurred at much lower jet coefficients but only as the initial jet surge was emitted. No indication was ever seen that successive secondary vortices were trying to develop in a periodic pattern. Cycling of the jet valve was found to produce a succession of these singular vortices in a periodic pattern.

The periodic secondary vortices were much more prominent for the baseline model and model III than for other configurations. In particular, model II, with the modified jet sweep angles produced secondary vortices that were poorly defined if even discernible. This was true despite extensive searching for a combination of blowing coefficient, dye port locations and angle of attack that would make the secondary vortices visible. Thus, the occurrence of the spin off vortices is apparently quite sensitive to the jet injection sweep angle. This sensitivity did not repeat for variations in dihedral angle as evidenced by Figure 22.

Karman Vortex Influences

The periodic nature of the spin off vortices suggested that the jet might be creating a blockage to the free stream flow which resembled a solid body and thus caused the shedding of Karman type vortices. This hypothesis was strengthened when the vortices were observed with heavy front port blowing at six degrees angle of attack and even at zero degrees angle of attack. The trajectory at $\alpha = 0°$ was quite different as the spin off vortices rotated about the y axis (but much more slowly than before) and traveled along it, but never turned upwards as described previously. Still the vortex appeared to

be similar to the earlier spin off vortices and its origin was obviously unrelated to the production of lift.

An experiment was arranged to investigate the relationship of the spin off vortices to the blockage effect and Karman vortices. The spacing of the spin off vortices was measured and the cylinder size consistent with Karman vortices at that spacing was calculated. The diameter of the required cylinder slightly exceeded the maximum thickness of the wing which was chosen as the cylinder diameter. This cylinder was then placed such that it was an extension of the wing tip and located chordwise at approximately the same location as the front jet port. If the spin off vortices resulted from Karman vortex type shedding, the flow field with the cylindrical extension should have also contained the same type of phenomena. It should be recognized, however, that a fluid jet in a cross flow will not shed vorticity in the same way as a solid body in a cross flow. In particular, the jet entrains much of the vorticity into the two vortices within the jet. Likewise the separation that occurs behind the solid body is not necessarily present in the wake of the jet. If separation does occur in the jet wake, it would exist only in the potential zone very near the jet orifice.

The flow field which resulted from the cylindrical wing tip extension is shown in Figure 24. At this flow velocity ($Re_c = 5.8 \times 10^3$, $Re_d = 7.0 \times 10^2$) dye collected in regularly spaced dye pools which were then swept upward in the wake. However, these dye pools had no rotational motion and did not follow the same trajectory as the

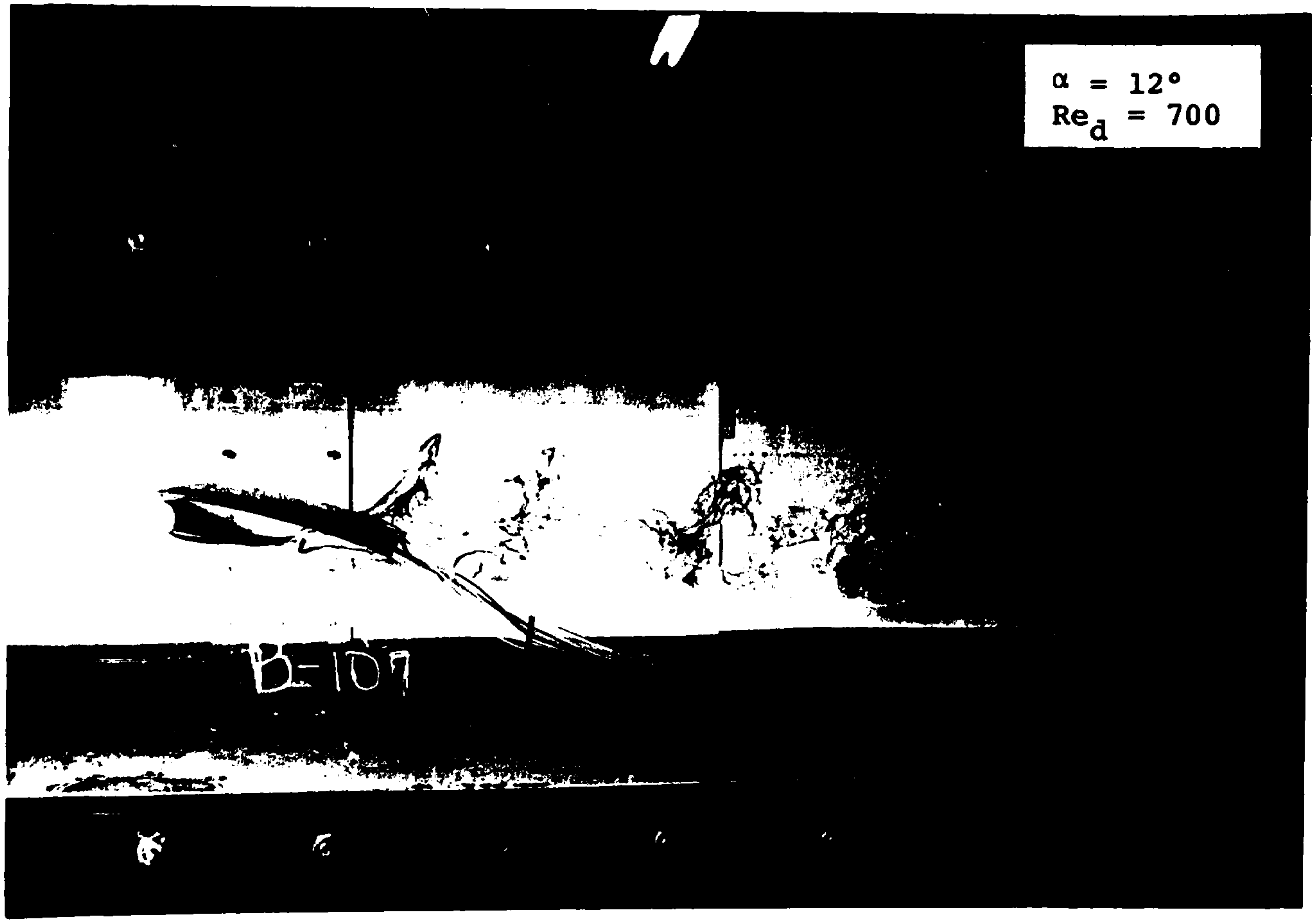


Figure 24. Cylindrical Tip Extension Flow Field

spin off vortices. Since the dye ports were located on the end and bottom of the wing tip, the pooling seen in Figure 24 may represent only one side of the vortex street. The dye pools all appear to have been swept up from the lower side of the wing or cylinder wake.

It is believed that the dye pooling seen in Figure 24 is the result of periodic Karman vortex shedding from the cylinder. However, the lack of rotational motion perpendicular to the free stream in Figure 24 is very important. The secondary vortices are evidently produced as a result of jet effects more complex than a simple blockage of flow. And, while pooling of the dye indicates that periodic vortex shedding may supplement the production of spin off vortices, the spin off vortices are not Karman vortices themselves. Further, conditions that should produce Karman vortices are not sufficient to produce spin off vortices independent of the jet's influence.

It was expected that model IV with its vertical slit jet shape would create more blockage and perhaps create the secondary vortices at lower jet coefficients. It was found however that the vertical slits greatly increase the turbulent mixing in the interaction region and the dye was quickly dispersed. Spin off vortices, if present, were never apparent in the flow field due to this increased mixing.

Entrained Secondary Vortices

Another type of periodic secondary vortex development was observed while testing model IV, the vertical jet slit model. Heavy blowing ($C_\mu = 0.23$) through the aft jet port caused periodic formation

of these secondary vortices on the upper surface of the wing just above the aft jet port. The vortices would then move away from the wing apparently being entrained in the jet vortices. The secondary vortices continued to travel as though one end were attached to the wing tip vortex and the other end to the jet vortices. The secondary vortices would stretch as the jet vortices and the wing tip vortex moved apart, but rotation would continue. Photographs of this flow field did not show this phenomenon in detail due to the tremendous mixing caused by this jet configuration. Figure 25 shows the vortices faintly and Figure 26 illustrates the observed structure. The rotation of the secondary vortices was in the same direction as the wing tip vortices and upper counterrotating vortex. The pattern leads one to believe that some vorticity from the wing tip vortex is entrained in the jet vortex and becomes a part of that system. Thus, these vortices were called "entrained secondary vortices." Mixing was so great that the dye in the jet vortex diffused before it intersected the wing tip vortex in the wake region.

These vortices were not seen except for heavy aft port blowing from this particular configuration. The method of generating them was different from the spin off vortices (aft port blowing versus front port blowing), and their trajectories were different also. Hence the entrained secondary vortices are felt to be a separate phenomenon from the spin off vortices.

The entrained secondary vortices are similar to the periodic vortices seen by Butkewicz (76) in the wake of both a jet in a cross

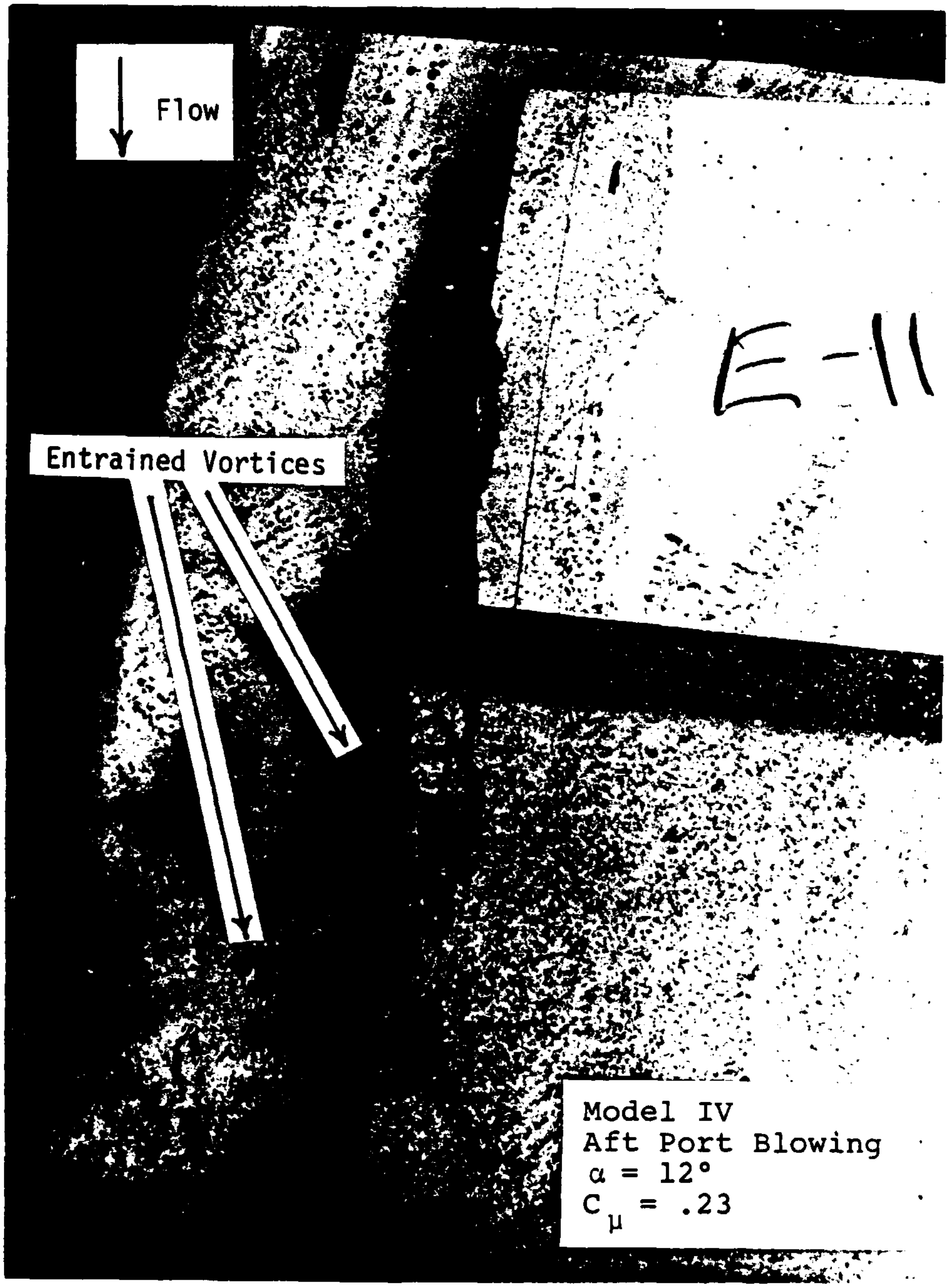


Figure 25. Entrained Vortices

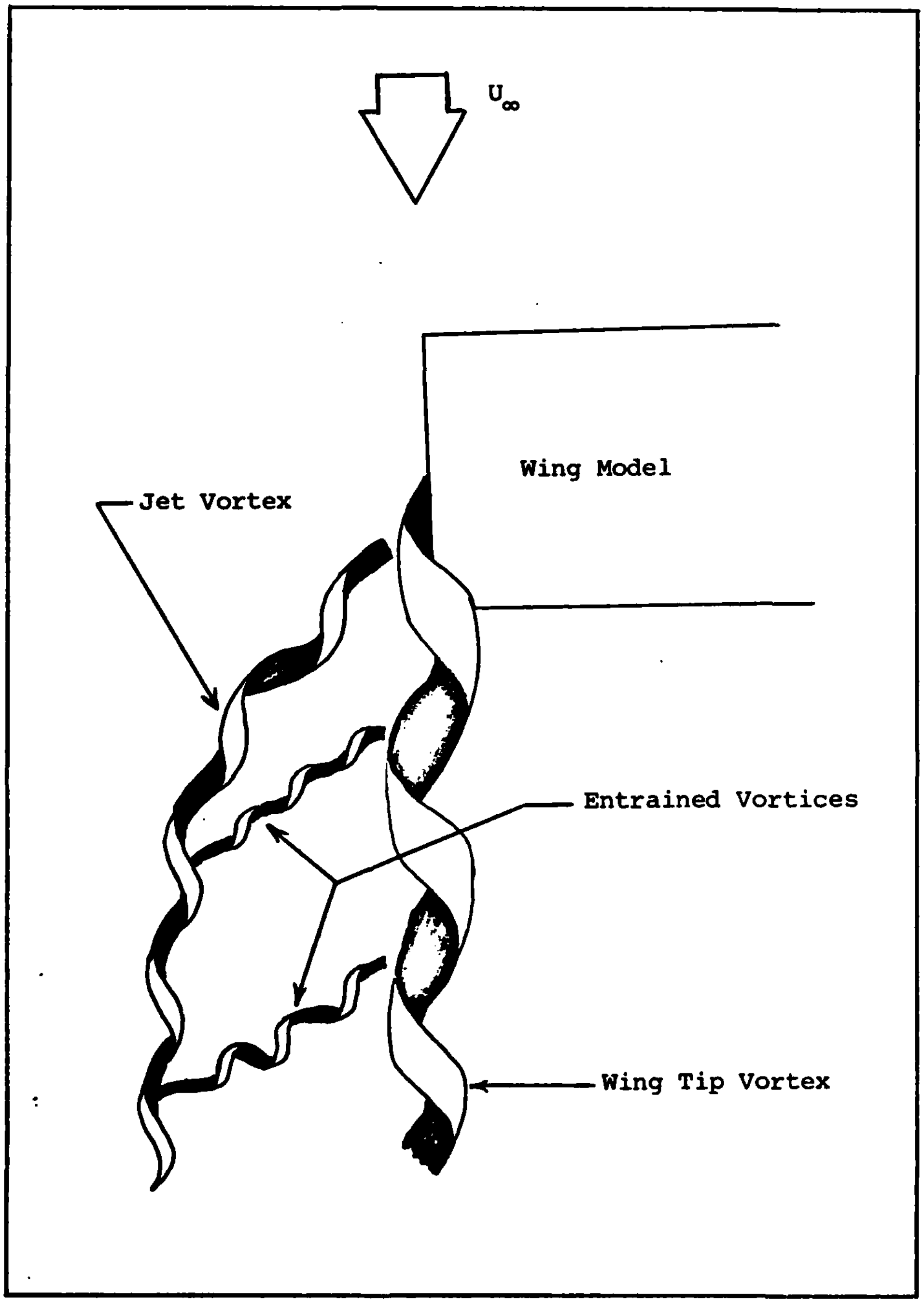


Figure 26. Structure of the Entrained Vortices

flow and a simulated jet (a porous tube with suction to create entrainment) in a cross flow. Butkewicz measured the shedding frequency of the vortices behind the jet and compared it to the shedding frequency for a Karman vortex street behind an equivalent circular cylinder. The shedding frequency for the jet was slightly less than for the cylinder, but did follow the same trends with respect to Reynolds number variations. The Reynolds number based on jet equivalent diameter in this experiment was much lower than Butkewicz used and lies outside the range of his data. Extrapolation of his data, however, predicts a frequency very near to that observed for the entrained secondary vortices (approximately 0.3 cycles per second). Butkewicz used the spacing and strength of the periodic vortices to predict the mass entrained by the jet and found that the entrainment was quite large, particularly for small diameter jets. He also found that mass entrainment in the jet and the periodic structure of the jet wake were closely related to each other.

Effect on Wing Tip Vortex

Both types of secondary vortices draw a portion of their energy from the wing tip vortex system and consequently reduce its intensity. They also create more effective mixing in the wake region and thus hasten the decay of the entire system. These influences should be beneficial in reducing the induced rolling moment of the wing tip vortex. However, heavy blowing was required to make both types of secondary vortices visible in the flow field. Because the blowing was heavy, significant vortex dispersion would probably have been achieved

even without the secondary vortices. Additional work needs to be done in order to identify a configuration which can produce the secondary vortices at lower jet coefficients and establish their effectiveness independent of heavy blowing. While this definitive proof of their effectiveness is needed, it is certainly possible that the secondary vortices were actually present in these tests for a broader set of conditions than have been identified. Failure to observe them at other conditions does not necessarily mean that they were not present only that they were not visible. Unseen secondary vortices may actually be an important part of the vortex dispersion seen at lower jet coefficients and with distributed jet blowing.

The secondary vortices which were observed are important contributors to the accelerated diffusion of vorticity into the wake surroundings. This can be hypothesized from the observed flow field , but it can also be shown directly by considering the Helmholtz equation for the time rate of change of vorticity which was discussed in Chapter II. The $(\vec{\omega} \cdot \nabla)\vec{u}$ term in that equation is zero for two-dimensional flow, and thus vortex spreading is simply a viscous diffusion process. This term is nonzero when a component of vorticity is aligned with a velocity gradient. In the typical wing tip vortex the strongest component of the vorticity vector, by far, is the x direction component which is aligned with the free stream. Unfortunately the velocity gradient in the x direction is quite small and $(\vec{\omega} \cdot \nabla)\vec{u}$ is still a weak contributor to vorticity spreading. However, the contribution of this term should be greatly increased by

the production of secondary vortices such as were seen in this experiment. These vortices were originally aligned with the radial direction and their contribution to the $(\vec{\omega}\cdot\nabla)\vec{u}$ term is $\omega_r \frac{\partial \vec{u}}{\partial r}$. Of course $\frac{\partial \vec{u}}{\partial r}$ is typically quite large in the vortex, larger than the velocity gradient in any direction. Thus, $\omega_r \frac{\partial \vec{u}}{\partial r}$ will greatly increase the magnitude of $(\vec{\omega}\cdot\nabla)\vec{u}$ and consequently the rate at which vorticity is spread. As was described earlier, the stretching of the spin off vortices was very evident, and this observation gives further credence to the hypothesis that $(\vec{\omega}\cdot\nabla)\vec{u}$ has become very effective as well as indicating that this term (the vortex stretching term) is well named. It is for these reasons that secondary vortices are considered to be very important in producing accelerated vortex decay. In addition to the research mentioned earlier on developing secondary vortices at lower blowing rates, much research is needed to establish the effect of Reynolds number on secondary vortex formation and to identify ways of producing them at flight conditions.

4. Jet Effectiveness in Vortex Dispersion

As was discussed in Chapter II, the most conclusive measurement of wake vortex alleviation is the reduction in induced rolling moment which the alleviation scheme is able to achieve. Changes in the size of the vortex core and changes in rotational velocity are good indications of vortex alleviation, but do not guarantee reduced rolling moment on following craft. With such uncertainty surrounding the ultimate influence of quantifiable data regarding wake vortex structure, it should be obvious that the interpretation of flow

visualization data on wake vortex effects is fallible. The best one can do is compare observed vortex dispersion and hopefully identify a set of configurations that offer the best prospects of reductions in induced moment. Further wind tunnel or water tow tank testing can then establish their relative merits.

While the degree of observed vortex dispersion is the best measure of vortex alleviation in this type of test, that criteria is still a subjective one, very difficult to judge. Intense mixing may lessen the observed rotational structure by replacing a strong laminar vortex with an equally strong but undetected turbulent vortex. Unsteady influences may not cause large changes in the near field wake, but may trigger Crow instabilities that will amplify and cause early destruction of the vortices in the far field. With these limitations in mind one returns to an alleviation criteria based on the degree of observed vortex dispersion--whether that dispersion is due to mixing, wing tip and jet vortices interactions, or secondary vortex influences. The following analysis used that criteria to develop general guidelines for vortex alleviation and jet configurational influences.

General Guidelines for Vortex Alleviations

The influence of the jet vortices when they intersected the wing tip vortex and interacted with it was very effective on breaking up the wing tip vortex. Figure 14a (see page 71) showed this very dramatically, as does Figure 27, which is model III with distributed blowing. Each time the interaction could be created, an obvious

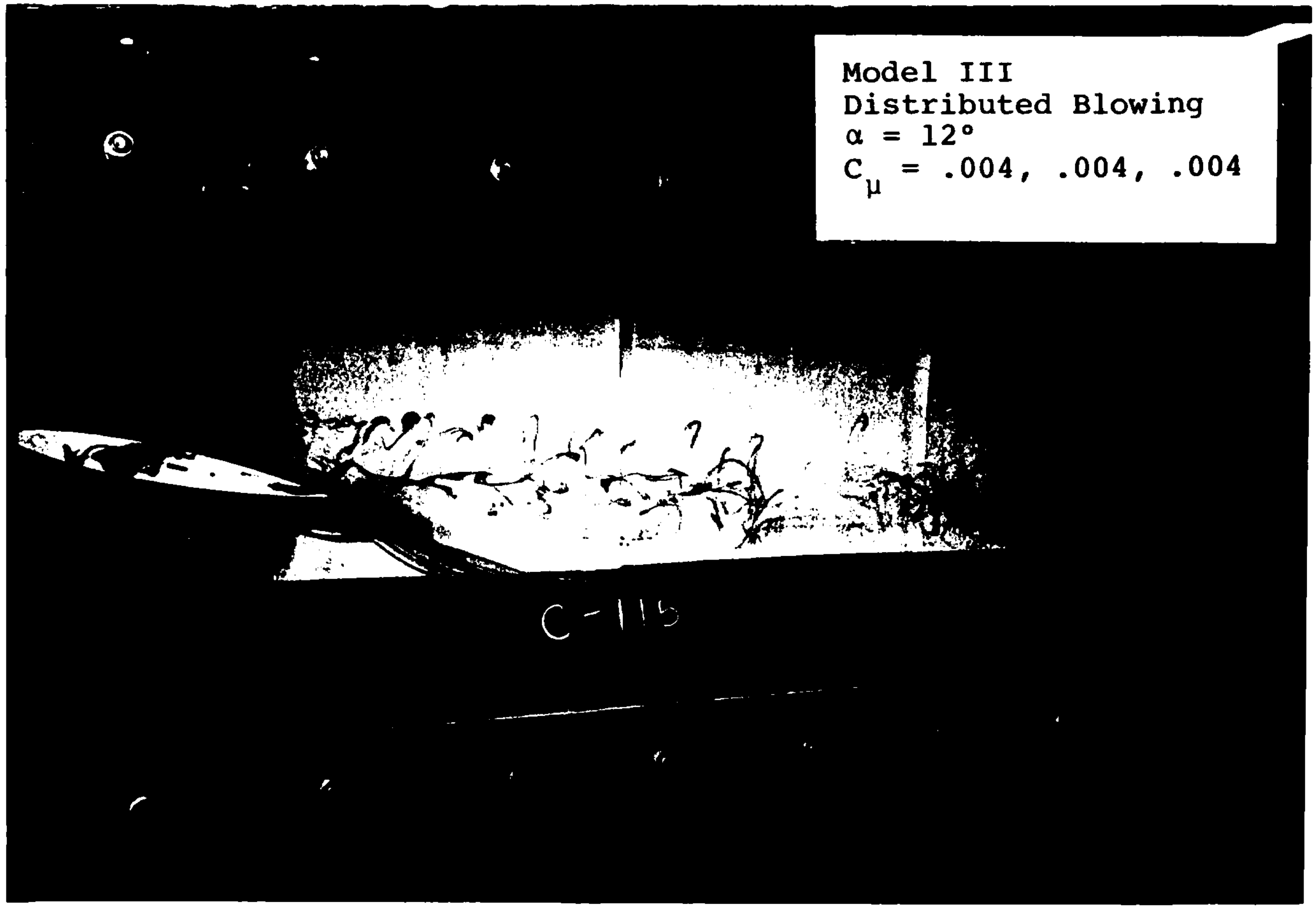
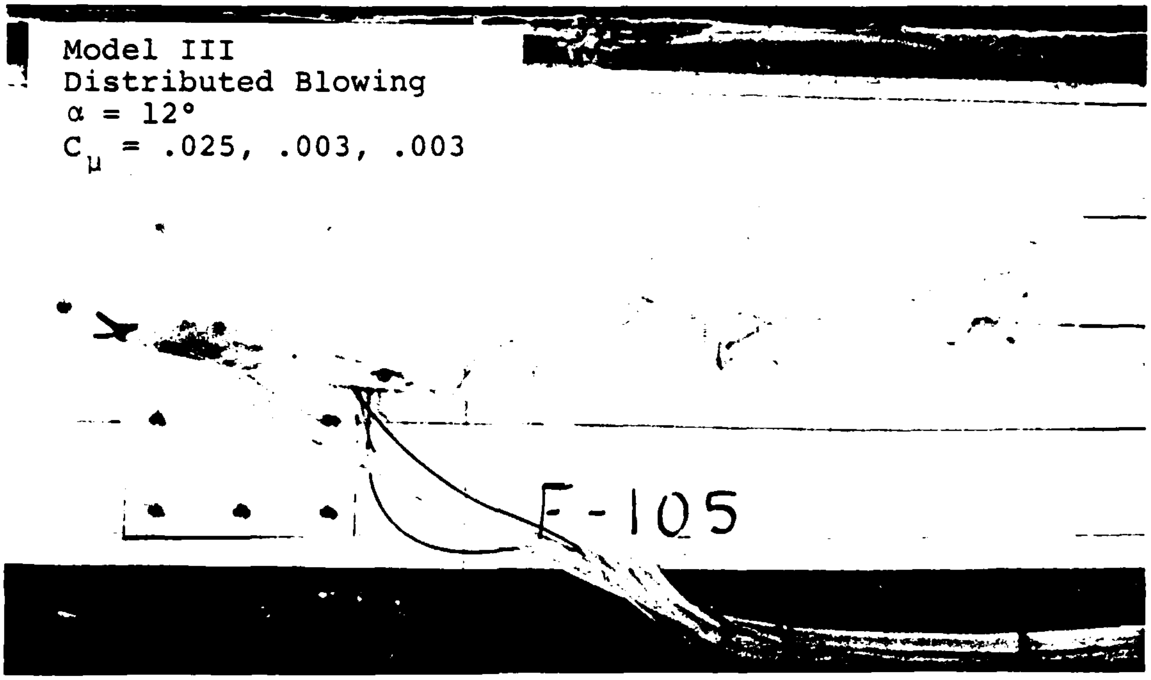


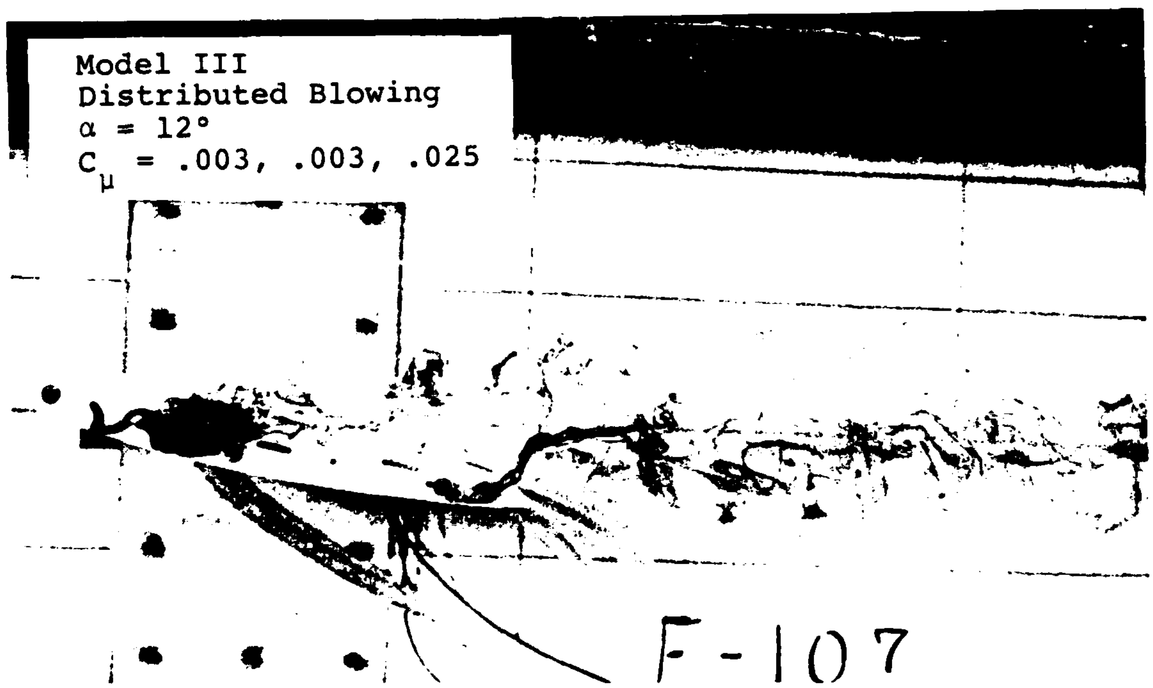
Figure 27. Dispersion Due to Vortex Interaction

dispersion of the wing tip vortex was observed. Generally, the interaction was with the jet vortex rotating opposite to the wing tip vortex and neutralization would be expected in that case. However, the similar rotating jet vortex, which was seldom seen in the lifting case, may also have a favorable influence, as has been seen in research with wing fins (49).

The second general finding was that distributed blowing with the largest jet coefficient at the front port and smaller jet coefficients at the middle and aft ports seemed to be the most effective method of dispersing the vortex. As was seen in Figure 16 (see page 74), concentrated blowing through any one port allowed a portion of the rolling up vortex to develop unimpeded. Thus, distributed blowing was recognized early as a key to vortex dispersal. The other advantage of distributed blowing was that more jet vortices are created and the opportunity for alleviating vortex interactions is increased. Figure 28 compares two different blowing distributions that use all three ports. Figure 28a has jet coefficients of 0.025, 0.003, and 0.003 front to rear. The vortex dispersal is much greater than for Figure 28b, which has the same jet coefficients in reverse order (0.003, 0.003, and 0.025). The blowing in Figure 8 (see page 60) distributed concentrated blowing at the front over a larger area (C_μ = 0.011, 0.011, and 0.003) and was nearly as effective as that in Figure 28a. The blowing patterns of both Figure 28a and Figure 8 are much more effective than single port blowing at a higher blowing coefficient (e.g., Figure 21, page 81).



a. Blowing Concentrated Toward the Front



b. Blowing Concentrated Toward the Rear

Figure 28. Comparison of Blowing Distributions

The forward sweep of the front blowing port produces more intense mixing than does blowing from the other ports. The increased mixing could possibly cause one to miss seeing the rotational motion that is present. However, detailed observations of a great many vortex patterns repeatedly showed that distributed blowing which was more concentrated toward the front produced the greatest vortex dispersion.

The last general guideline is an obvious one—vortex dispersion improves steadily as jet coefficient increases. Very small jet coefficients (C_μ = 0.001) cause minor changes in the vortex structure, such as increased mixing inside the vortex core, but no change in its rate of diffusion to the surrounding fluid. These small jet coefficients can cause some trajectory motion, however, as has been discussed. Jet coefficients on the order of 0.01 are much more effective at dispersing the vortex (e.g., Figure 28a) if distributed properly and cause greater trajectory changes. Jet coefficients that are 0.1 greater effectively disperse the vortex for nonoptimum blowing distribution and produce two types of unusual secondary vortices.

<u>Configurational Influences</u>

The most significant configurational influences have previously been discussed in the sections dealing with the observed phenomena. They will briefly be summarized here.

The most noticeable effect of jet sweep angle was its influence on the production of secondary vortices. Model II could not produce the secondary vortices despite much effort to do so. Other

differences, particularly with respect to vortex dispersion characteristics and vortex trajectory, were not detected. Continued testing on the effect of jet sweep injection angle should concentrate on isolating the effect of sweep angle from injection location. Reverse sweep on an aft jet port and forward sweep on forward ports should be tried.

The significant effect of the vertical jets, model IV, were to create tremendous turbulent mixing and to produce the entrained secondary vortices. Despite the heavy mixing, rotation was still observable in the wake, although dye streaklines were very diffuse and poorly defined. This rotation was great enough to indicate that the model was not as effective as still photographs indicated, nor was it as effective as models with horizontal jet slits.

The dihedral model, model III, behaved similarly to the baseline model in all respects. This similarity points out the limitations of flow visualization in detecting minor flow field changes. Optimization of design features such as jet injection dihedral angle will require wind tunnel testing with an instrumented model in the wake of the wing. The testing of two models which provided similar results was very fortuitous, however. The additional data provided confirmation of results in both vortex dispersion and vortex trajectory. Additionally, it confirmed that the secondary vortices were a real phenomenon not limited to one unique tip configuration.

CHAPTER VI

A COMPUTATIONAL MODEL OF WAKE VORTEX ROLL UP WITH DISCRETE JETS

A simple mathematical model of wake vortex roll up including discrete jet effects provided valuable insight into the flow phenomena seen in water tunnel testing. The model is very idealized; it is two-dimensional, inv cid, and accounts for jet influence solely by the inclusion of the counterrotating jet vortices. Yet these limitations are certainly warranted by the tremendous complexity of the flow field seen in Chapter V. Tri-dimensionality, localized nonuniform mass injection, and multiple turbulent jets in a translating and rotating laminar stream are just three of many complexities that would have to be included to calculate the true flow field. If such complexity could be set up in a program, the a priori prediction of two types of periodic secondary vortices would challenge even the most sophisticated programs. Thus the simple model discussed below was chosen as a more realistic approach, and it proved to be very useful.

1. The Computational Model

Wing Vortices Model

The roll up of a three-dimensional vortex sheet into concentrated vortices can be investigated by examining the time dependent roll up of an equivalent array of two-dimensional line vortices. Figure 29 shows the classical trailing vortex system for a finite wing where the individual trailing vortex strengths $g_i(y)$ are

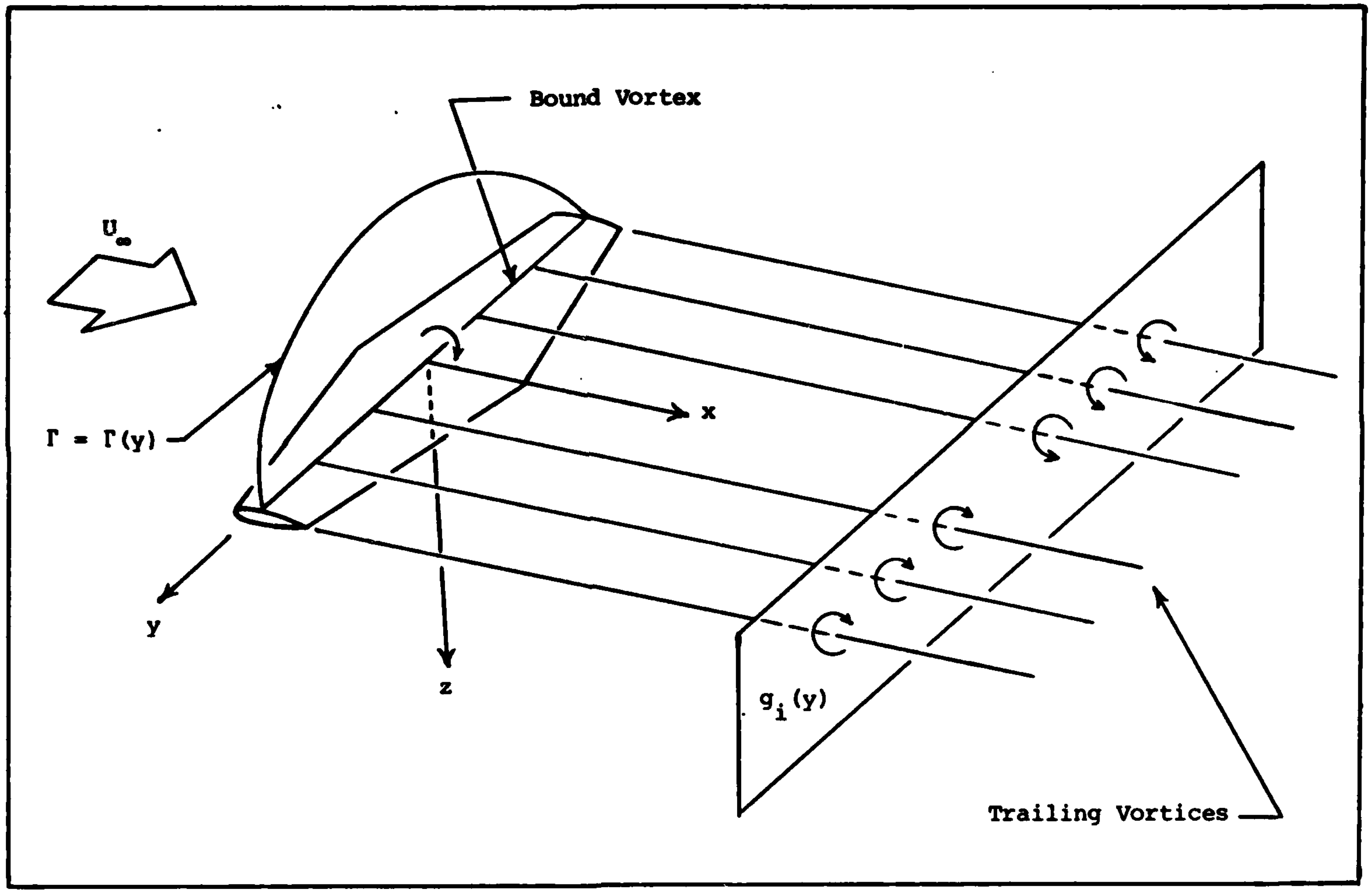


Figure 29. Three-Dimensional Wing Model

functions of the spanwise lift distribution or spanwise variation in circulation, $\Gamma(y)$. An elliptical lift distribution was used throughout this investigation. The equivalent set of two-dimensional vortices is arrived at by eliminating the bound vortex on the wing and extending the trailing vortices to infinity in the negative x direction. The Biot-Savart law which was discussed in Chapter II is then used to calculate the velocity of each line vortex as the sum of the velocity components induced by all other line vortices in the model. Mathematically, the Biot-Savart law becomes

$$\frac{dy_i}{dt} = \sum_{j \neq i}^{m} \frac{g_j}{2\pi} \frac{z_i - z_j}{(y_i - y_j)^2 + (z_i - z_j)^2}$$

$$\frac{dz_i}{dt} = -\sum_{j \neq i}^{m} \frac{g_j}{2\pi} \frac{y_i - y_j}{(y_i - y_j)^2 + (z_i - z_j)^2}$$

The calculated velocities are then used to determine the motion of each line vortex over a small interval of time, and velocity calculations are then repeated based on the new vortex positions. The roll up of the resulting two-dimensional vortex sheet as time progresses will closely resemble the three-dimensional roll up development as distance behind the wing increases.

Westwater (79) first used this method in 1936, and found that the line vortices rolled up into smooth spirals in the vicinity of the wing tips. However, several later attempts to reproduce Westwater's results have found the vortices to move chaotically rather than forming a spiral structure. Moore (80) reviewed these results and indicated that Westwater's early success with the model may have been

due to large time steps and Euler integration combining to produce smooth but inaccurate results. He concluded that the chaotic motion in later studies was due to vortices which closely approach each other in the vicinity of the wing tip. To avoid this problem he developed guidelines for combining line vortices as they migrated to the inner spiral of the rolling up vortex sheet. This method gave smooth spiral structures with no inherent numerical errors. The roll up patterns are quite detailed and show remarkable agreement across variations in method of discretization, number of vortices used to simulate the vortex sheet, and time step. Chorin and Bernard (81) and Kuwahara and Takami (82) also avoided chaotic motion of the vortices by introducing an artificial viscosity that limited vortex velocities inside a selected cut-off radius, and thus eliminated the large vortex excursions associated with close approaches. Bloom and Jen (83) used the method of Kuwahara and Takami to calculate vortex roll up and found their vortex location data to compare favorably with experimental results. Recent improvements on this model include the use of piecewise continuous vorticity distribution rather than discrete line vortices (84).

The program used in this investigation was a modified version of a program presented by Chow (85). One improvement to the wing vortex model of Chow was in the original locations of the discrete vortices. The vortex sheet is divided into a number of spanwise intervals, and in the original program a discrete vortex with the total strength of the sheet over that interval is located at the center of the interval. Since the sheet strength (γ) is not

constant, the vortices within an interval would induce a velocity at the center of the interval. This self-induced velocity was neglected by Chow, but he pointed out that more realistic results could be attained by placing the discrete vortex at the point in the interval where the self induced velocity should be zero. This was done and helped to delay the occurrence of chaotic motion which Chow found in the tip region at higher values of time. However, even better results were obtained by originally placing the vortices at the centroid of vorticity over the interval they represent as had been done by Moore (80) and by Clements and Maull (86). Consequently, this method was used in all calculations. Another major improvement to the program was the incorporation of Moore's criteria for the merging of vortices in the wing tip spiral. This modification completely prevented chaotic motion in the tip region. Other improvements included the use of double precision arithmetic and an option to discretize the system with vortices of equal strength as opposed to intervals of equal spacing that contained vortices of variable strengths. The program was run with no discrete jet influences and checked almost identically with Moore's results.

Jet Vortex Model

The dominant influence of the wing tip jets, especially outside the immediate vicinity of the jet port, is the set of counterrotating vortices which are produced. To model this influence a pair of two-dimensional counterrotating vortices was placed outboard of each wing tip as shown in Figure 30. These jet vortices then affected, and were

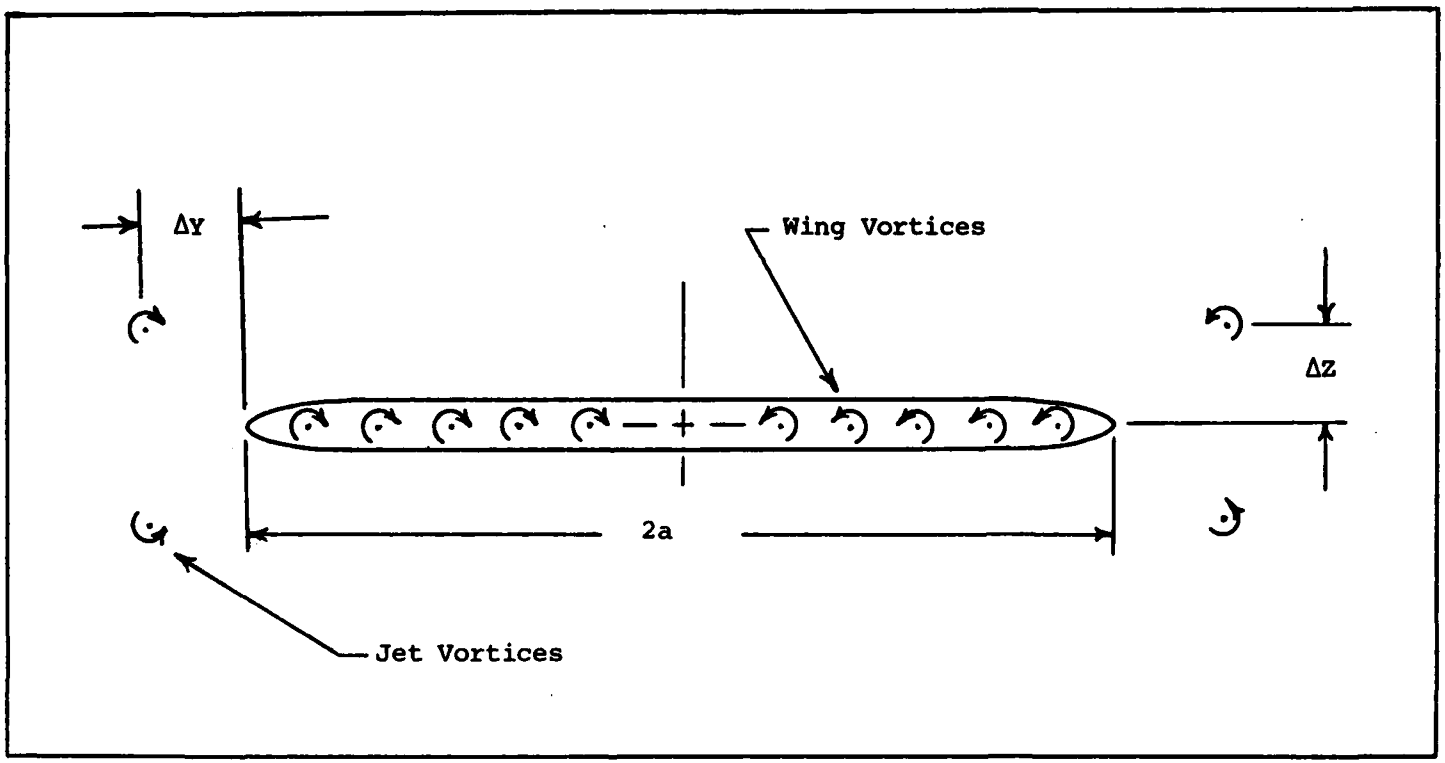


Figure 30. Jet Vortex Model

affected by, each vortex in the wing vortex system acccrding to the Biot-Savart law. The main output of the program was the change in the roll up of the wing vortices due to the effects of the jet vortices. However, the jet vortices also moved due to the influence of each other and the wing vortex system. Their trajectories were output and proved to be very useful in analyzing the results.

The strength of the jet vortices varied according to the data presented by Krausche, Fearn, and Weston (64) for a jet ejecting at 90 degrees to the free stream. Decreases in strength due to diffusion were included in the math model and the two levels of blowing for which data was available (R = 4 and R = 8) were both used. These jet velocity ratios equate to very reasonable jet coefficients. For single port blowing from the water tunnel model, velocity ratios of 4 and 8 give equivalent jet coefficients, C_μ, of 0.012 and 0.047. These jet coefficients represent moderate blowing in the water tunnel. No attempt was made to simulate multiple port blowing in this two-dimensional model.

2. Computational Results

General Findings

The goal of this computational investigation was to better understand the effect of the discrete jets and to verify flow patterns seen in the water tunnel. Since the water tunnel used a half span model, some half span cases were run on the computer to compare to full span cases. As expected, little difference was seen except near

$y = 0$ where vertical movement was less for the half span cases. The following results are for full span calculations but should be comparable to water tunnel results in the wing tip region.

A baseline arrangement of jet vortices was selected in order to examine the effect of initial jet vortex position in a systematic way. The baseline arrangement has DY which is $\Delta Y/a$ equal to 0.05 and DZ which is $\Delta Z/a$ equal to 0.10. A baseline value of dimensionless time was also chosen in order to systematically compare different vortex roll up rates. As in Chow, time is made dimensionless by

$$T = \frac{t\ \Gamma_0}{2\pi a^2}$$

where Γ_0 is the circulation in the plane of symmetry of an elliptically loaded wing. The baseline time was chosen to be $T = 0.15$ which corresponds in three dimensions to a point approximately 5 chord lengths behind the wing. This is far enough away from the wing that the two-dimensional model is realistic and yet is still within the viewing area of the water tunnel.

Figure 31 is a comparison of the vortex roll up pattern at $T = 0.15$ for a wing with and without the jet vortices included. Jet vortices are originally located at the baseline position. As can be seen, the vortex sheet of the wing with no jet influences has rolled up into the nice spiral found in earlier work. On the other hand, the wing with the jet vortices included has rolled up into a spiral that is less well defined with uneven spacing between vortices in the tip region. This lack of definition is due to numerous vortices being

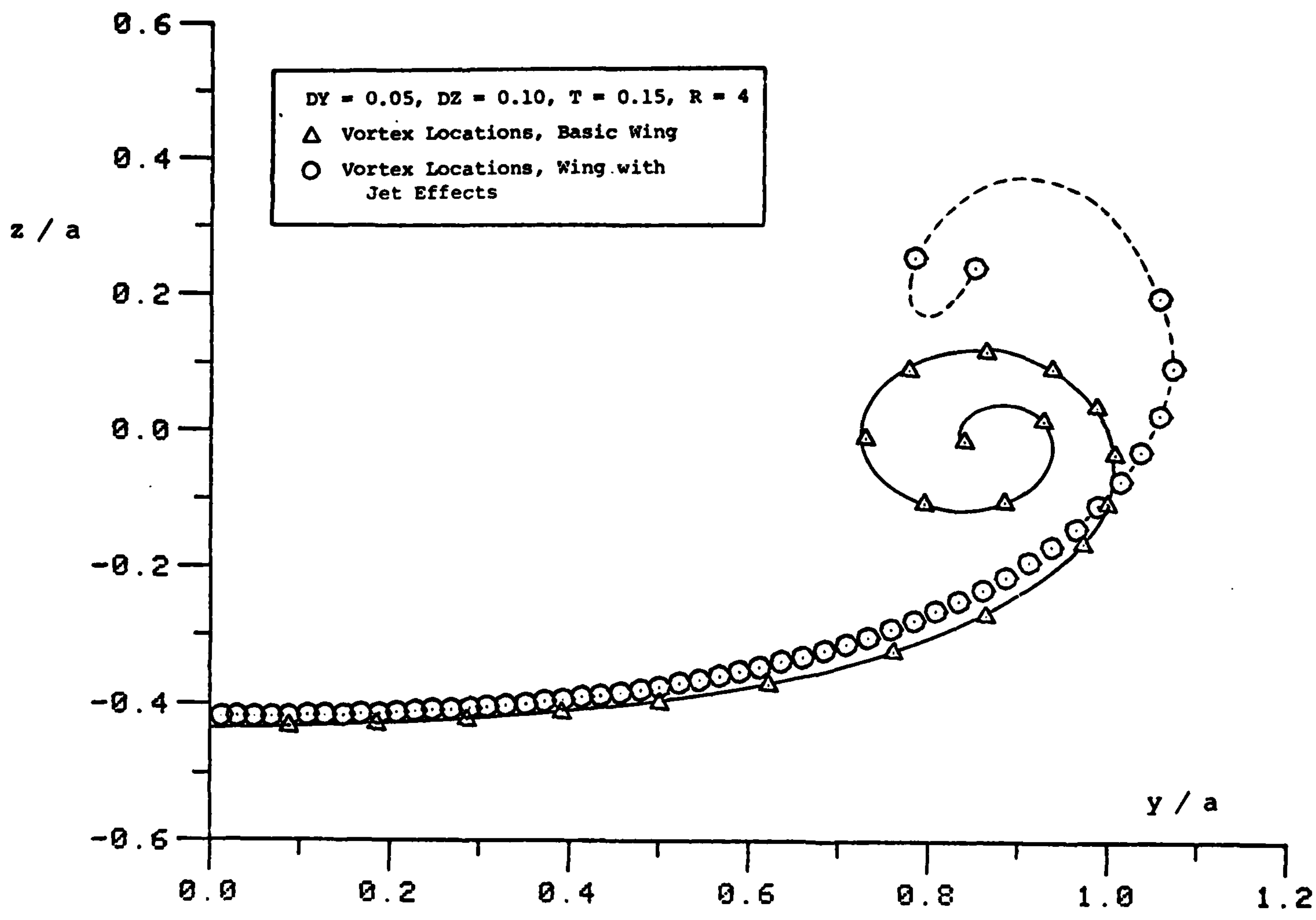


Figure 31. Roll Up with Jet Effects

combined in the tip region according to Moore's criteria. Despite the lack of detail for the second spiral, two things are immediately obvious in the plots. First, the jet has caused the vortex core to be shifted upwards significantly. Comparing the last vortex in each line shows that the shift caused by the jet is greater than 20 percent of the wing semispan. This is a very sizeable shift and agrees favorably with the similar shift seen in several of the water tunnel tests. Secondly, one sees that the interior vortices of the wing vortex system with jet effects included have not moved downward as much as those in the basic wing. This decrease in effective downwash is once again a promising result with respect to expected aerodynamic improvements. The last important item in Figure 31 is not as obvious--the jet has lessened the strength of the rolled up portion of the vortex sheet. Following Moore (80), the rolled up portion of the sheet is defined as the part between the center of the spiral and the point where the tangent is last parallel to the z axis. Performing this comparison one finds that the tip vortex for the basic wing contains 71.4% of the total vorticity on the semispan while the vortex for the wing with jets contains only 57.7% of the total vorticity. This finding is also very encouraging.

Figure 32 is a plot of the same data seen in Figure 31, but the trajectory of the counterrotating vortex pair has been added. The upper vortex which rotates similar to the wing vortex system becomes entangled in the rolling up vortex sheet and would probably not be seen as a separate structure in the water tunnel. The lower vortex

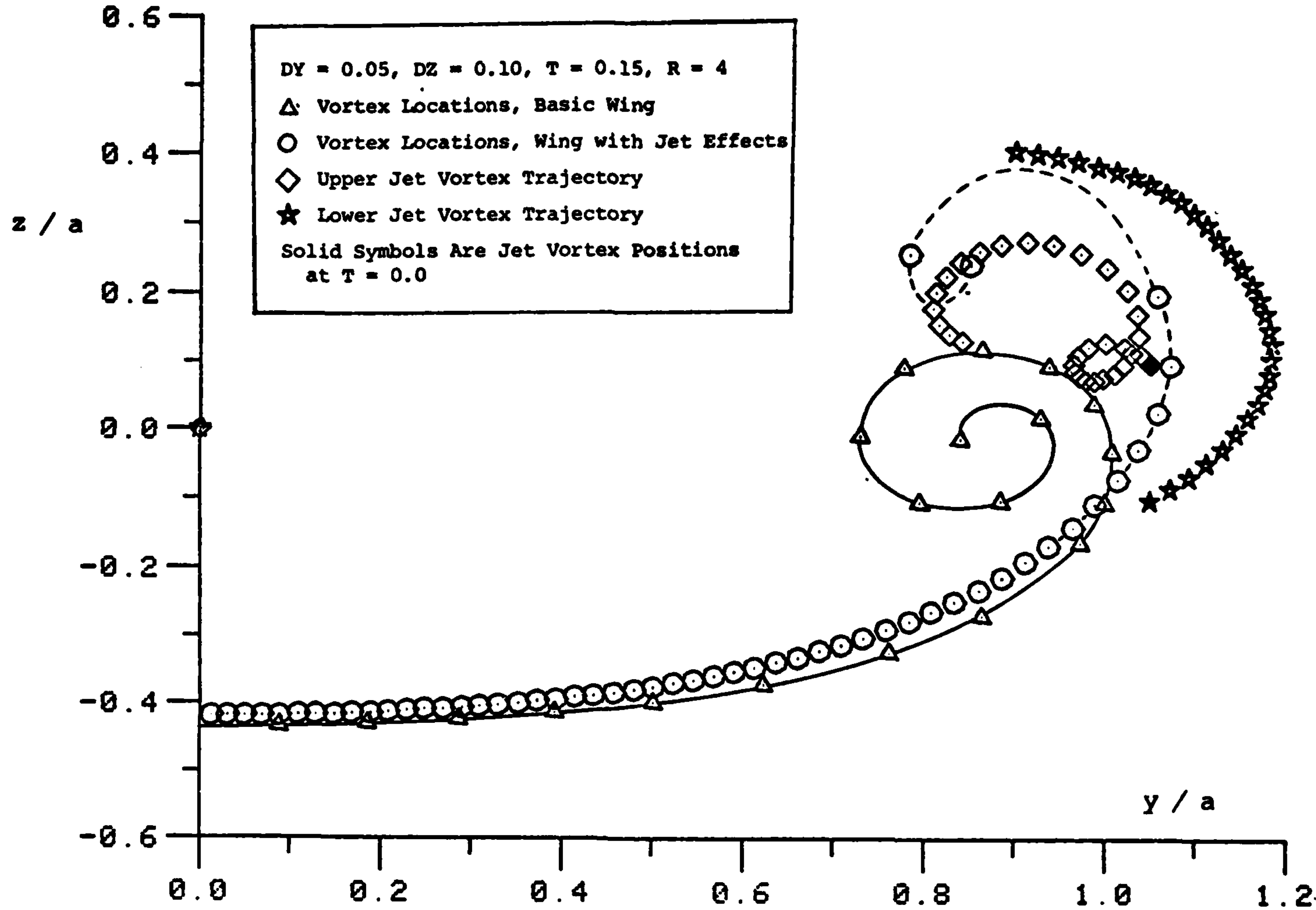


Figure 32. Jet Effect Roll Up with Jet Trajectories

which rotates opposite to all the others rotates around the system exactly as was seen in most water tunnel observations.

The lack of detail on the rolled up vortex shown in Figures 31 and 32 is typical of those cases where the jet caused significant vortex shift and/or substantial reduction in rolled up vortex strength. In those cases where the jet vortices were less effective the resulting roll up was defined much better. For example, Figure 33 compares the basic wing roll up with the roll up for jet vortices initially at DY = 0.15 and DZ = 0.10. Both vortex sheets form a very nice spiral, and the core of the jet modified vortex is elevated much less than was seen in Figure 31. The strength of the jet modified vortex is 64.2% of the total vorticity which is less than the unmodified vortex strength, but greater than was seen in Figure 31. The decline in jet effectiveness is due to the jet vortices originally being located further outboard than was used earlier. As can be seen from their trajectory, they are further removed from the rolling up wing vortex and consequently less influential.

As would be expected, the decrease in downwash achieved by the jets can be enhanced by magnification of the vortex in the counterrotating pair which rotates opposite to the wing system. Figure 34 points this out very dramatically. The jet vortex which rotates similarly to the wing vortex system has been eliminated, and the downwash as measured by the travel of vortices near the plane of symmetry is greatly reduced. This downwash reduction would be beneficial to the wing aerodynamic performance. Possible methods of

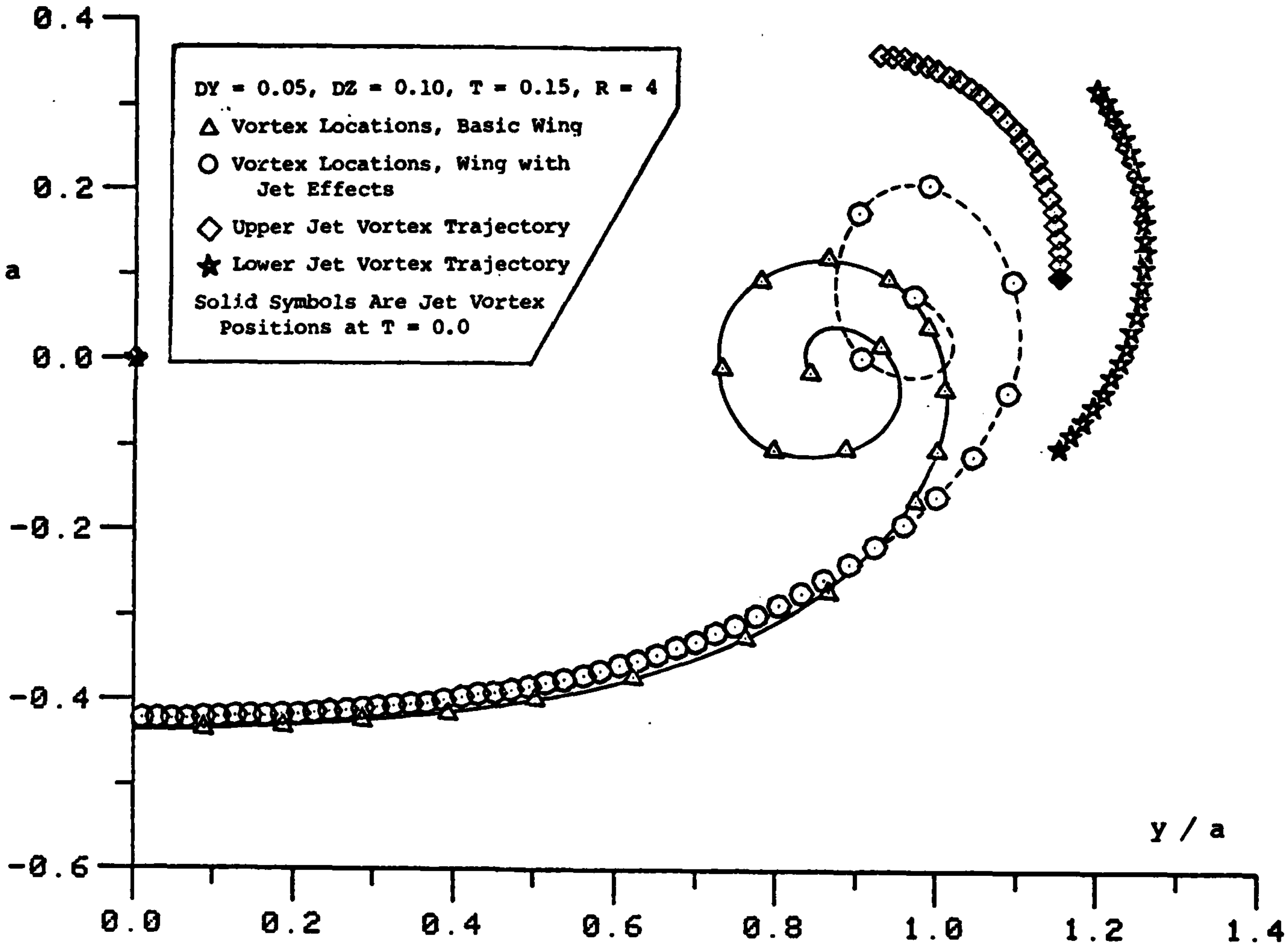


Figure 33. Roll Up with Jets Far Outboard

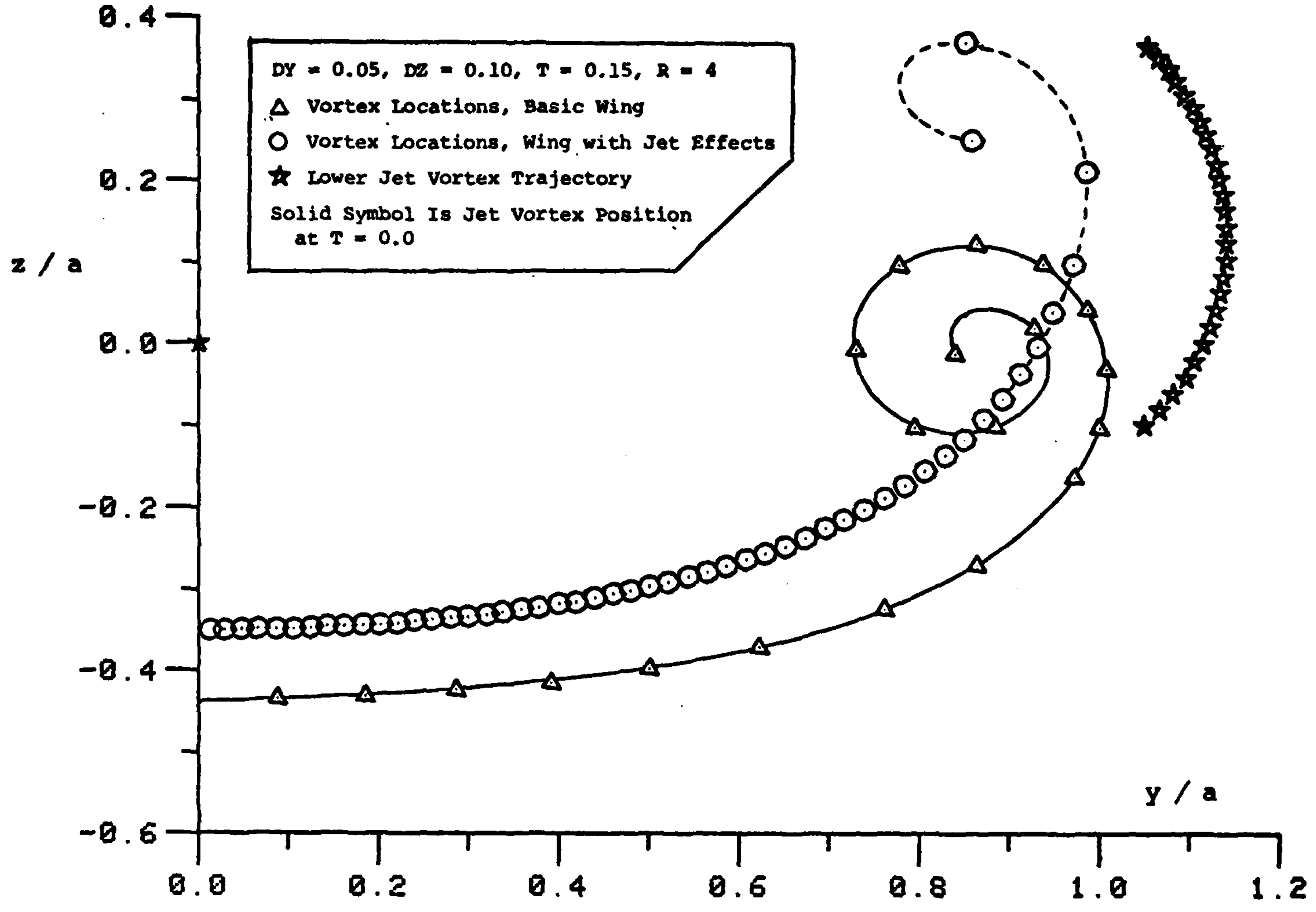


Figure 34. Roll Up with Unsymmetric Jet Vortices

singular vortex magnification include triangular or other nonsymmetric jet ports and rotation of the jet fluid prior to ejection.

Effect of Jet Vortex Initial Location

The initial location of the counterrotating vortex pair strongly affects their trajectory and interaction with the wing tip vortex. As seen earlier, an extreme outboard location (DY = 0.15) causes the vortex pair to rotate around the tip vortex but to be too far removed from it to be effective. This was also seen in the water tunnel experiments.

Other influences of location were also found to occur. Figures 35 and 36 summarize the influence of initial jet vortex position on the strength of the rolled up portion of the wing tip vortex. Also shown is the rolled up vortex strength for no jet blowing. One immediate observation is that the jet vortices have a favorable influence on alleviating the rolled up strength wherever they originate. This was almost universally true; only some locations where the counterrotating vortices were inboard of the tip (an unrealistic situation) showed any increase in wing tip vortex strength.

The optimum position, however, for the counterrotating vortices to originate is near the selected baseline conditions (DY = 0.05, DZ = 0.10). Additionally, the rolled up strength is apparently more sensitive to the vertical spacing between the vortices (DZ) than it is to the distance of the vortices from the wing tip. This is especially true as the counterrotating vortices closely approach each other. The

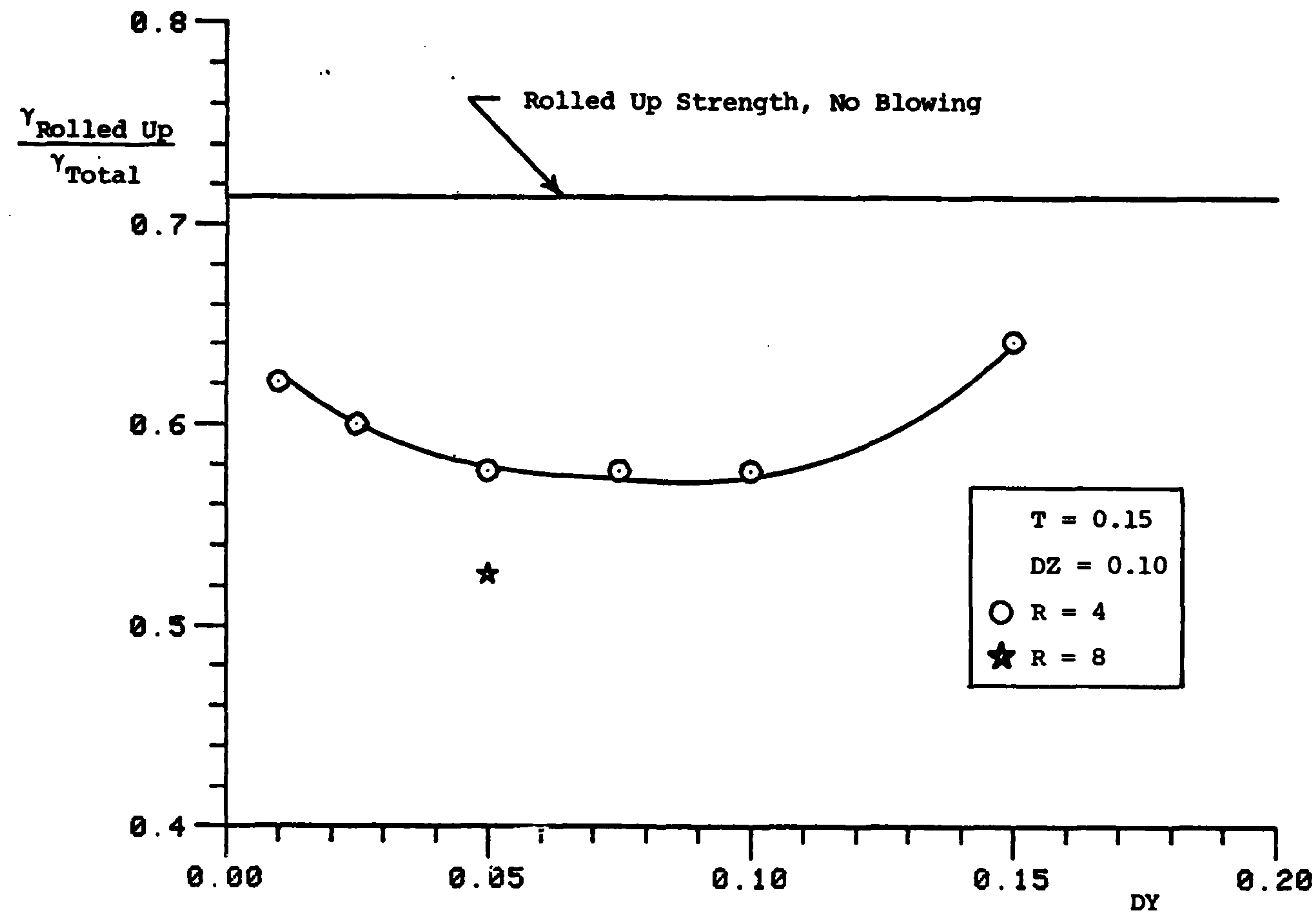


Figure 35. Effect of Spanwise Spacing on Rolled Up Strength

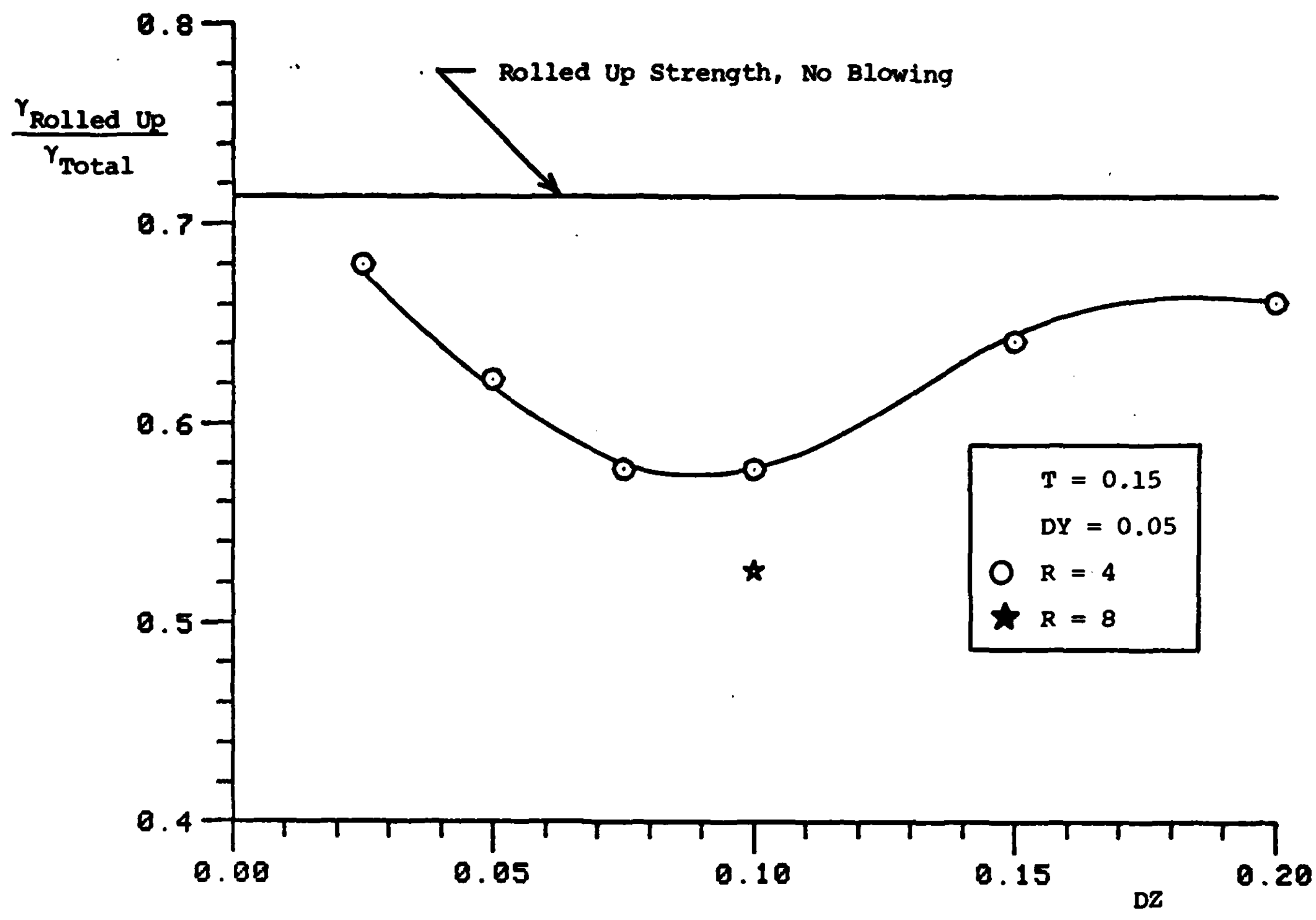


Figure 36. Effect of Vertical Spacing on Rolled Up Strength

reason for this can be seen in Figure 37 where DY = 0.05 and DZ = 0.025. In this case the influence of each vortex in the counterrotating pair is concentrated on the other member. Thus the pair moves together very rapidly out of the roll up region completely. At some point they approach each other so closely that they cross; at this point the model would be invalid since viscous effects would become very important as well as the nonlinear vortex interactions. This two-dimensional calculation probably overpredicts the movement of the vortices with respect to the three-dimensional case. In the real flow field, the momentum of the cross flow would exert a strong influence on the jet vortex trajectories and probably prevent, or at least retard, this type of paired drifting. Yet, the model does point out the importance of involving the jet vortices with the wing vortex system rather than with each other.

The initial position of the jet vortices also has a significant impact on the amount of stretching that is done on the wing vortex sheet. If DY is small and DZ is also small, but above the level where the paired influences dominate, this stretching can be quite large. Figure 38 compares the initial roll up of the basic wing with that of a jet equipped wing with the initial jet vortices at DX = 0.025 and DY = 0.025. At T = 0.005, the basic wing has already rolled up into the first spiral while the jet equipped wing has lifted the last vortex in the sheet quite high and is still stretching the rest of the sheet.

It is also interesting to note that the jet vortices in Figure 38b did not pair off and move out of the roll up region even though

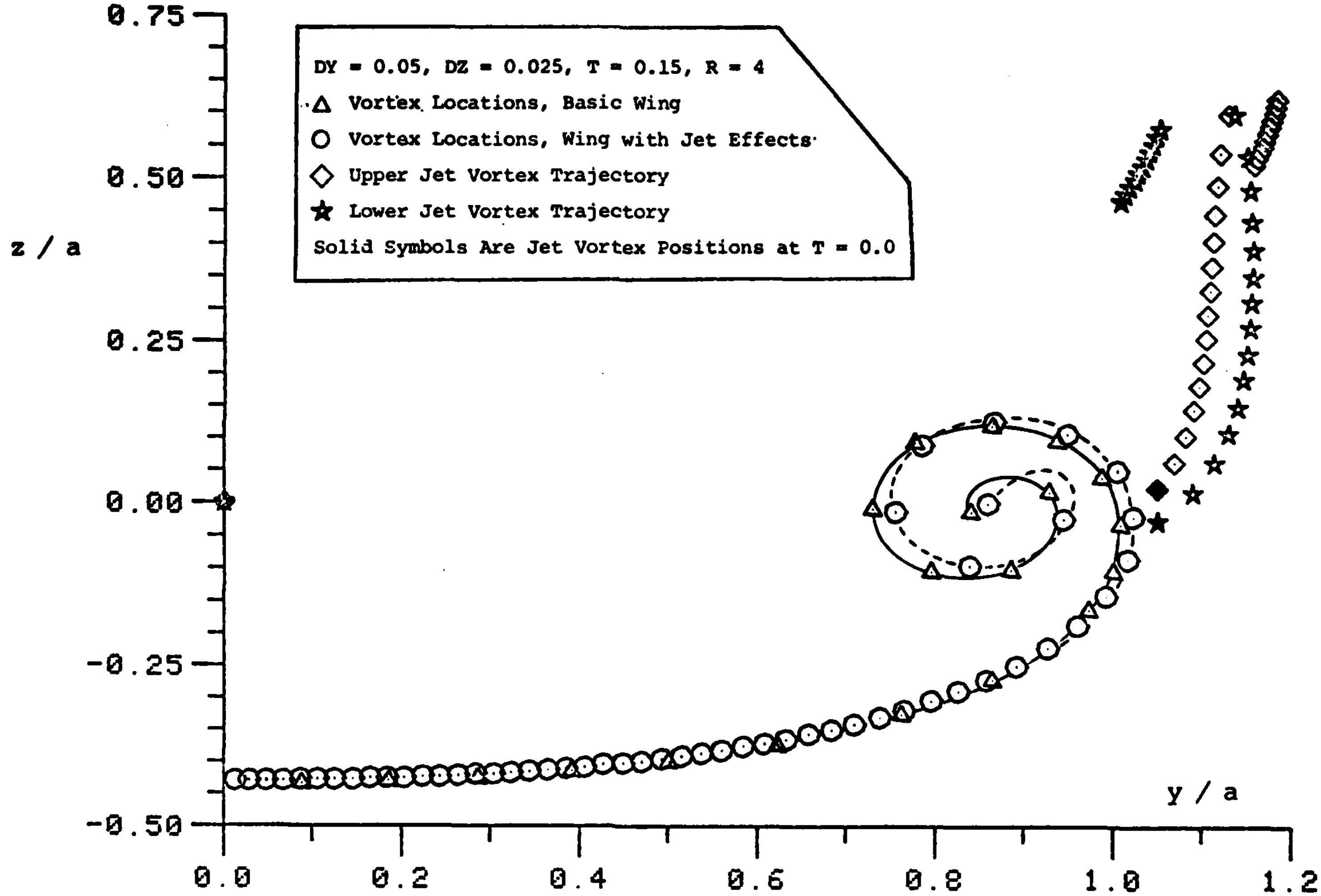
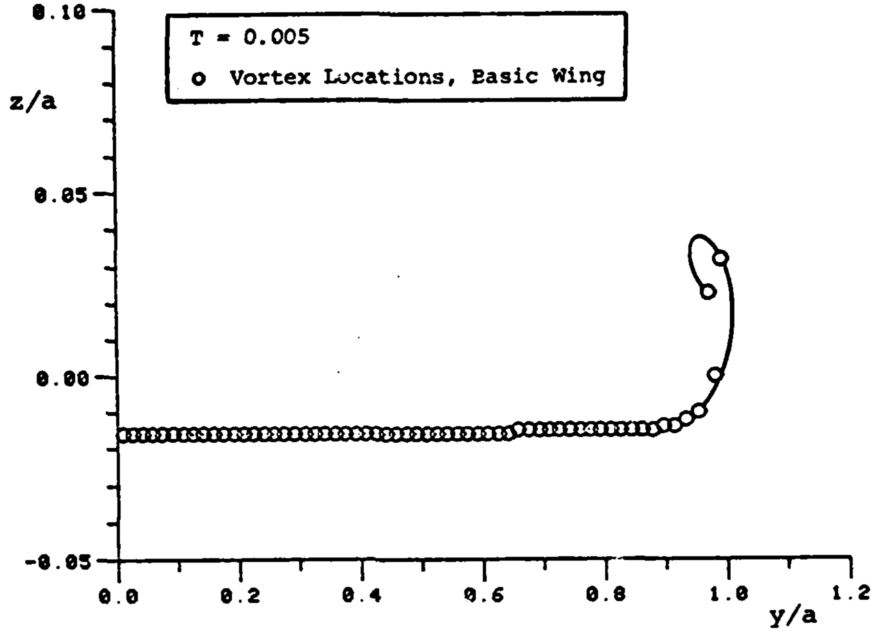
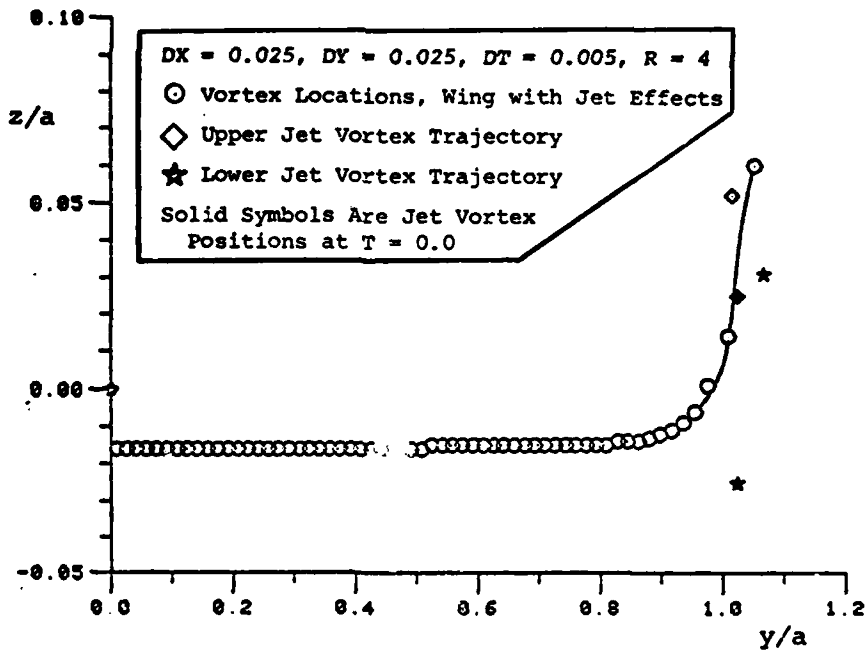


Figure 37. Roll Up with Paired Drifting of Jet Vortices



a. Without Jet



b. With Jet

Figure 38. Initial Stretching During Roll Up

they were as close originally as those shown in Figure 37. Obviously the position with respect to the wing tip is also important in controlling the degree of interaction between the jet vortices and the wing tip vortex.

The stretching of the vortex sheet early in the roll up process was not the only way that the jet vortices affected the wing tip vortex. In particular, the roll up with the jet vortices at the baseline position showed little stretching during the early stages. Later, however, after the upper jet vortex moved inward and its trajectory is became a tight spiral (see Figure 32 on page 113) the stretching began and the influence of the jet vortices was quite strong.

The importance of initial jet vortex position is clear, but controlling the initial position must be possible in order to take advantage of the lessons learned. Some control of trajectory was noted in the experimental part of this investigation, but no control of the vertical spacing, DZ, was either attempted or observed. Fortunately, the data of Krausche Fearn and Weston (60) show that vertical spacing is a function of jet injection angle. This influence should be considered in the design of future jet ports.

Effect of Jet Vortex Strength

The effect of increasing jet vortex strength is to increase the elevation of the vortex core and to decrease the strength of the rolled up wing tip vortex. Figures 35 and 36 presented the rolled up

strength for jet vortices with a jet velocity ratio, R, equal to 8, and located at the baseline position. The strength was 52.6% of the total vorticity which is a reduction of 26.3% from the strength of the no jet rolled up vortex. Higher jet vortex strength also magnifies the stretching of the wing vortex sheet which was described previously.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Discrete wing tip jets have demonstrated the capability to reduce the intensity of a rolling up wing tip vortex. Both water tunnel experiments and a computational model of the flow field showed the following significant changes.

1. The apparent strength of the wing tip vortex is significantly reduced for moderate levels of blowing ($C_\mu \sim 0.01$).

2. The wing tip vortex as modified by the discrete jets is shifted upwards in the wake over a wide range of jet conditions.

3. The counterrotating pair of vortices produced by the jet, and in particular the vortex rotating opposite to the wing vortices, were often observed in the wake wrapped around the wing tip vortex system.

4. The key to reducing the intensity of the wing tip vortex is to produce auxiliary vortices which then interact and merge with the wing vortices.

Additionally, the water tunnel results revealed two types of periodic secondary vortices which could be produced by the discrete jets at certain unique blowing conditions. The two types were "spin off vortices" which periodically developed in the rolling up tip vortex but quickly spun outboard and above the wing and "entrained vortices" which was a set of periodic vortices laterally connecting the wing tip vortex and the jet vortices. The secondary vortices, and

in particular the spin off vortices, are oriented such that they will greatly accelerate the spreading of wake vorticity. The accelerated spreading is a result of the vortex stretching term, $(\vec{\omega}\cdot\nabla)\vec{u}$, in the Helmholtz equation for the time rate of change of vorticity. Other unsteady effects were also seen particularly with front port blowing.

The water tunnel also showed that the discrete wing tip jets could shift the location of the wing tip vortex outboard or cause an "effective increase in aspect ratio" for jet coefficients as low as 0.001. Increases in turbulent mixing within the jet core were also seen at these very low jet coefficients.

Jet configurational results showed that distributed blowing concentrated toward the front of the model was most effective in minimizing the wing tip vortex. Vertical jet slits introduced tremendous mixing into the wake region but did not seem as effective at reducing rotation as did horizontal slits. The periodic secondary vortices were observed only while a single unique port was being used. It was not determined if port location or port sweep angle was the critical parameter with regard to secondary vortex production.

Further research on discrete wing tip jets is needed in order to substantiate and quantify the beneficial effects which have been seen in this investigation. Wind tunnel experiments at higher Reynolds number are needed to determine if the observed changes in wake vortex structure will be effective in reducing the induced rolling moment on a model in the wing wake. Wind tunnel experiments on the aerodynamic performance of wings with discrete jets should also

continue. Special emphasis should be given to quantifying the effect of the jets on wing induced drag.

Jet configuration optimization should continue as a part of the wind tunnel investigation. If tunnel size permits, a model with remote control of jet sweep injection angle and jet dihedral injection angle would greatly accelerate the optimization process. Continued water tunnel testing on jet configuration should concentrate on isolating the effect of jet location and jet sweep particularly with regard to the production of secondary vortices. Additional visualization data is also needed on the effect of jet shape including numerous small circular jets grouped close to each other to form a larger jet sheet and the effect of spinning the jet as it leaves the jet port.

Discrete wing tip jets have demonstrated tremendous potential for improving the flow field near a three-dimensional wing tip and in its wake. If that potential can be developed and exploited significant progress can be made toward a synergistic design capable of increasing lift and reducing drag during cruise flight and alleviating wake vortex intensity during takeoff and landing operations.

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Fred Thomas Gilliam, Jr. was born on 30 October, 1947, in Knoxville, Tennessee, the son of Fred Thomas Gilliam, Sr. and Louise Elrod Gilliam. He attended elementary and junior high school in Chattanooga, Tennessee, and graduated from high school in Antioch, Tennessee, in 1965. In 1969, he graduated from the University of Tennessee with the Bachelor of Science degree in Aerospace Engineering, and received a commission as an officer of the United States Air Force. After working for a short period in the DC-9 performance group for the Douglas Aircraft Company, Long Beach, California, he entered active duty at Wright-Patterson AFB, Ohio. Following an assignment as an aircraft performance engineer for the Aeronautical Systems Division, he entered the Air Force Institute of Technology and was awarded the Master of Science degree in Aeronautical Engineering in December, 1974. He then served as Instructor and Assistant Professor of Aeronautics at the United States Air Force Academy, Colorado. In 1978, he entered the University of Tennessee Space Institute in Tullahoma, Tennessee and subsequently received the Doctor of Philosophy degree, with a major in Aerospace Engineering, in August, 1983. Presently he is serving as Chief of the Reentry Systems Branch, Deputy for Operations, at the Arnold Engineering Development Center in Tullahoma, Tennessee.

Major Gilliam is married to the former Miss Linda Williams. They have four children, Andy, David, Jamie, and Travis.

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